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Section 8

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8. Fate and Transport of Constituents

8.1 General

This section addresses the sources, fate, transport, and bioaccumulation of the constituents of concern for the Rest of River, focusing mainly on PCBs and, to a lesser extent, PCDDs/PCDFs. It includes discussion of the processes that affect the fate and transport of these constituents, potential sources of the constituents, and significant mechanisms that govern the fate and transport of the constituents within the Housatonic River. Numerous physical, chemical and biological processes affect chemical fate and transport. However, not all of the processes are of major importance; some fate and transport processes control the dynamics observed in the system, while others have minimal or negligible impacts. Identifying this hierarchy of processes is fundamental to understanding the distribution and fate of PCBs.

The remainder of this section is presented in the following major subsections: Section 8.2 contains a brief description of sampling activities specific to evaluating fate and transport. Sections 8.3 through 8.5 address the physical, chemical, and biological characteristics of the system that affect chemical fate and transport. Section 8.6 presents information on potential sources of PCBs and PCDDs/PCDFs to the system. Section 8.7 discusses the composition of PCBs in the system. Finally, Section 8.8 provides information on mechanisms that affect the fate, transport, and bioaccumulation of PCBs in the Rest of River, while Section 8.9 presents a brief discussion of mechanisms affecting the fate and transport of PCDDs/PCDFs. The next section of this RFI Report (Section 9) presents a conceptual model of the Housatonic River that integrates the major mechanisms that control fate and transport of PCBs and PCDDs/PCDFs in the Rest of River.

8.2 Description of Sampling Activities

In addition to the various media-specific sampling activities described in Sections 3 through 7, a number of sampling programs were conducted specifically to evaluate fate and transport characteristics of sediments and PCBs within the Rest of River. These programs include the following (along with cross-references that identify the subsections where the results are discussed):

- 1997 GE Study of Cohesive Sediment Erosion Properties. Erosion properties of cohesive sediments were measured in cores collected from various impoundments along the Rest of River (Section 8.8.1.5).

- 1999-2002 EPA Cross-Section Surveys. Periodic river channel cross-sectional surveys were conducted at a number of locations to evaluate bed elevation changes (Section 8.3.5.6).

- 2000-2002 EPA Toe Pin Measurements. Elevation readings at toe pins installed in 2000 were taken periodically to evaluate bank erosion rates (Section 8.8.1.9).

- 2001-2002 GE/EPA Partitioning Study. A sampling program was conducted to evaluate PCB partitioning characteristics in sediments and surface water (Section 8.8.1.2).

- 2001-2002 EPA River Meander Study. Field surveys were conducted along various bends in the River to evaluate short-term channel movement, while digital shorelines were developed from historic aerial photography to facilitate a long-term assessment of River meandering (Section 8.8.1.10).

- 2002 EPA Bed Load Sampling. Sediment bed load (i.e., coarse-grained sediment being transported by the River current near the sediment-water interface) was sampled during a May 2002 storm event (Section 8.8.1.8).

8.3 Physical Characteristics of the System that Affect Fate and Transport

The physical characteristics of the Housatonic River significantly affect chemical fate and transport; these include:

- Watershed characteristics;
- Hydrologic and hydraulic characteristics; and
- Sediment transport characteristics.

8.3.1 Watershed Characteristics

Watershed characteristics largely control the Housatonic River's hydrologic response to precipitation intercepted by the watershed. Tributaries determine the spatial distribution of water and solids loading to the River and can be important determinants of chemical fate and transport. Tributaries deliver water, which acts to dilute waterborne chemicals, and solids that settle within the impoundments and backwaters.

Land use is the principal determinant of how a tributary network functions, in terms of both the hydrologic response to precipitation and the sediment loading delivered to a river. Agricultural lands generally produce higher sediment yields than forested areas and urbanized areas. The high percentage of impervious cover in urban and suburban areas produces a sharper hydrologic response to a given precipitation event than that from other land-use types. As discussed in Section 2, the Housatonic River watershed upstream of Great Barrington is mostly forested (71%) with urban, agricultural, and wetland areas ranging from 4% to 10 % of the watershed (Figure 2-14).

8.3.2 Groundwater Interactions

Groundwater has the potential to impact fate and transport within a watershed, both through discharge and recharge. Discharge of groundwater containing contaminants at high concentrations can cause accumulation of those constituents in the local sediments and a net flux to a river system. One potential interaction associated with groundwater is the impact of upward advective flux through contaminated sediments (i.e., groundwater seepage). This process can cause chemical constituents dissolved in interstitial waters to be transported to the overlying water column at a rate that is accelerated relative to diffusion. The rate of groundwater seepage is a function of the local hydraulic gradient and the hydraulic conductivity of the bed materials. Groundwater seepage within the Housatonic River is likely influenced by a number of factors, including sediment type, local topography and groundwater elevations, and the local effects of dams and their associated backwaters. No data are available to directly assess the seepage flux within the Rest of River area. However, because the hydraulic conductivity of the alluvial deposits within the region is typically low, the extent to which seepage flux causes accelerated transport of constituents dissolved in sediment pore waters is not expected to be significant.

8.3.3 Hydrology and Hydraulics

The timing and annual extent of precipitation, as both rain and snow, influence chemical fate and transport. Precipitation contributes both water and sediment, via soil erosion, to the River. The spring thaw, occurring between March and May, generates significant runoff from the watershed, with the largest floods of the year usually occurring during this period. The magnitude and duration of the spring floods depend on a number of factors, including areal extent and depth of the snowpack, soil and groundwater conditions, meteorological conditions, and amount of rainfall. Flow in the River is impacted by rainfall in various ways, with River flow depending on: spatial distribution, duration and intensity of rainfall; vegetative cover in the watershed; soil conditions; and groundwater conditions. Rare, intense storms (e.g., thunderstorms and tropical storms that have made landfall) produce large amounts of rain that can cause major high-flow events in the River during the summer and fall.

The geometry of a river channel and its slope affect fate and transport characteristics. As discussed in Section 2, between the Confluence and the WWTP (Reach 5A), the River is relatively shallow and fast-flowing, due in large part to the relatively steep slope of the channel. This flow regime results in a high energy environment and a coarse sediment bed, both of which affect transport of constituents that are bound to particulate matter. Downstream of the WWTP, the River slope decreases, producing a deeper and wider channel. This section is characterized by a broad floodplain and large areas of shallow backwater regions associated with Woods Pond Dam. These characteristics affect chemical fate and transport differently than does the steeper channel upstream, as the lower energy environment promotes deposition and accumulation of fine sediments as well as biological growth. Within Reach 7, the channel gradient is much steeper, resulting in large stretches where the River is shallow and fast flowing and sediments are characterized mainly by gravels and coarse sands. The River does become locally more quiescent in the relatively small backwaters associated with the three dams in Reach 7. At Rising Pond (Reach 8), the presence of the dam causes the River to become much deeper and wider, with lower current velocities. This flow regime promotes fine sediment accumulation, which affects the fate and transport characteristics of the system in this reach.

Water velocities in a river control the energy exerted at the sediment-water interface and, consequently, is the driving force for sediment resuspension, bank erosion, and channel meandering. The hydrologic characteristics of the Housatonic River Basin that affect velocities and sediment transport were described in Section 2. These include basin geometry and bathymetry (including bed elevation gradients), water flow, stage height, and bank elevation, as well as vegetation (both submerged macrophytes in the main channel and backwaters and emergent vegetation in the floodplain).

8.3.4 Water Temperature

Several physicochemical processes are affected by temperature, including diffusion, volatilization, and desorption from sediments. Temperature also affects a number of biological processes, which indirectly influence fate, transport, and bioaccumulation of constituents. These include phytoplankton dynamics, bioturbation, and the growth and metabolism of fish and other biota.

The water temperature measured during water column sampling efforts (discussed in Section 3) is summarized in Figure 8-1 for the major sampling stations along the Rest of River. The data exhibit no clear differences among the locations within Reaches 5 through 8 (panel a) and show slight year-to-year variations (e.g., 1998 appears to have been a warmer water year than 1999). Further, high frequency data (e.g., every 15 minutes) collected by R2 in 2001 and EPA between October 2001 and June 2002 (shown together in panel c of Figure 8-1) indicate moderate variability on daily and weekly time scales and further demonstrate the year-to-year differences. However, the predominant trend in the River's water temperature is the seasonal pattern, characterized by temperatures in the 0-5^{o} C range in winter and early spring, followed by an increase to 20^{o} C to 25^{o} C during the summer, and a subsequent decline in the autumn months.

Based on this seasonal trend, it would be expected that the rates of kinetic processes such as diffusion, volatilization, and the extent to which hydrophobic chemicals desorb from sediments would all be greater in the summer than in the winter (Chapra, 1997). Furthermore, the year-to-year variations in water temperature have the potential to impact metabolic rates of fish, resulting in differences in chemical uptake during the growing season. Temperature also affects the onset of spawning and has a significant effect on larval development and YOY growth rates. For example, in largemouth bass (a warm-water species), adults are active at temperatures above 10^{o} C and YOY fish do not feed below a temperature of 15^{o} C (R2, 2002).

8.3.5 Solids in the Sediment Bed

Due to their hydrophobicity, PCBs and other chlorinated organics preferentially partition onto solids. Consequently, the fate and transport of these chemicals are directly linked to the fate and transport of solids within the system. Sources of solids include both those generated outside the system (allochthonous) and those generated within the system (autochthonous). Sediments and associated PCBs and other chemical constituents are eroded from the channel and banks and transported downstream or onto floodplains under elevated flow conditions. Deposition of solids and associated chemicals occurs as river current velocities slow within the channel or floodplain due to changes in river flow, channel morphology, or the density of vegetation.

8.3.5.1 Allochthonous Sources

Erosional processes in the surrounding watershed generate sediment loads to the tributaries and main channel of a river. The magnitude of the annual sediment load to the River is affected by many watershed characteristics, including land use, vegetation type and density, soil properties, and the intensity and duration of precipitation. Loading of sediments to a river and its tributaries from watershed erosion is a nonlinear and episodic process, with the majority of the annual load typically occurring during a relatively small number of storm events each year.

Sediment loads to a river can be estimated using different methods, including: soil erosion equations; data-based methods using suspended sediment rating curves; and application of a watershed model. These provide a quantitative means of evaluating the magnitude of solids sources along the system; estimates are provided in Section 8.3.5.3.

8.3.5.2 Autochthonous Sources

Autochthonous solids, sometimes termed biotic solids, are those solids that originate within a system from primary production. Biotic solids are characterized by a variable percentage of organic matter in the form of lipids that serve as a reservoir for the partitioning of hydrophobic organic chemicals such as PCBs (Stange and Swackhamer, 1994). The most common autochthonous source of biotic solids in the water column is phytoplankton growth, which is promoted by high concentrations of nutrients and light. As phytoplankton grow, PCBs are scavenged from the dissolved phase and become associated with these solids. Subsequent settling of these solids serves to remove PCBs from the water column. Ultimately, the growth and settling of phytoplankton serve as a mechanism to convey PCBs from the water column to the sediments. Review of data and visual observations within the system suggest that significant primary production of phytoplankton occurs within Woods Pond. Therefore, it is expected that biotic solids play a role in the fate and transport of PCBs and other constituents in this area of the River. The dynamics of phytoplankton growth in the Housatonic River are discussed further in Section 8.5.2.

8.3.5.3 Suspended Sediment and Solids Loadings

Suspended sediment loadings were evaluated using data collected by GE and EPA from eight locations during 1989-2002[2]: East Branch at Hubbard Avenue Bridge (Coltsville), Dawes/Pomeroy Avenue Bridge, West Branch, Holmes Road Bridge, Sackett Brook, New Lenox Road Bridge, Woods Pond Headwaters, and Woods Pond Dam. These locations are representative of tributary sediment loading to the River from the Confluence to Woods Pond Dam, as well as sediment loads in the main channel. These data were used to develop sediment rating curves, which are mathematical equations that describe the relationship between TSS concentrations and flow rate. These curves are plotted on Figure 8-2. (Appendix E.2 provides a description of how the rating curves were developed.)

Annual sediment loads for these locations were estimated by using daily average flow rates from the period 1980-1999 and the sediment rating curves (i.e., Figure 8-2). The mean annual sediment loads that resulted from this analysis are presented in Table 8-1. It should be noted that there is a degree of uncertainty associated with the absolute loading values because there is variability contained in the data that the rating curves do not account for. An interesting spatial pattern in annual sediment load is seen between the Confluence and Woods Pond Dam. The sediment load increases by over 30% between Holmes Road Bridge and New Lenox Road Bridge. This increase could be due to several factors, including tributary loading, bed erosion, and bank erosion. From New Lenox Road Bridge to Woods Pond Dam, the annual sediment load decreases by more than a factor of two, with about half this decrease

[2] Data collected before 1996 were used in the solids loading analyses to provide a more robust data set. TSS concentrations are not affected by the changes in sampling and analytical methods that were a factor in deciding not to use the pre-1996 PCB data for the spatial trend analyses in Section 3.

occurring in Woods Pond. This decline in sediment loading suggests that significant deposition occurs over this reach.

Table 8-1. Solids Loads and Sediment Yield within and Upstream of Reaches 5 and 6

Location	Drainage Area (mi^2)	Mean Annual Load (MT/yr)	Mean Annual Sediment Yield (MT/mi^2-yr)
East Branch at USGS Gage in Coltsville	58	786	14
East Branch at Dawes/Pomeroy Avenue	69	2180	32
West Branch	61	1,520	25
Holmes Road Bridge	132	3,160	24
Sackett Brook	11	280	26
New Lenox Road Bridge	147	4,170	28
Woods Pond Headwaters	169	2,890	17
Woods Pond Dam	169	1,700	10

Note:
MT/yr = metric tons per year

Net erosion processes in the drainage areas of the three tributaries (i.e., the East Branch, West Branch, and Sackett Brook) can be quantified by calculating the sediment yield, which is the annual sediment load per unit area (Table 8-1). The sediment yields for the three tributaries are similar, varying by less than 30%. This result indicates that the net erosional processes in these three drainage areas are similar, which is consistent with their similarities in watershed land use and topography.

The USGS conducted a sediment loading study between Great Barrington and Ashley Falls from March 1994 through September 1995 (USGS, 2000). The annualized sediment load at Great Barrington was 3,800 metric tons per year (MT/yr), which corresponds to a yield of 14 MT/mi^2-yr (drainage area of 280 mi^2). The USGS study also estimated loads for the Green River, which is a tributary to the Housatonic River between Great Barrington and Ashley Falls, with a drainage area of 51 mi^2. The annualized load for the 18-month study period on the Green River was 1,570 MT/yr. This load corresponds to a sediment yield of 31 MT/mi^2-yr, which is within a factor of two of the three tributaries in Reach 5. These values indicate that the sediment yields within Reaches 7 through 9 are similar to those in Reaches 5 and 6, which is expected given the similarities in land use.

8.3.5.4 Physical Properties of Sediments

Sediment bed grain size decreases significantly from the Confluence to Woods Pond, which is consistent with the decreasing channel gradient across this reach (see Section 2). As channel gradient decreases, current velocities (and associated bottom shear stresses) generally decrease and the sediment bed becomes dominated by finer materials. As described above in Section 4, the sediment bed in Reaches 5A and 5B is primarily composed of non-cohesive (sandy) sediment, while most of the bed in Reach 5C and Woods Pond is composed of cohesive (muddy) materials. Backwater sediments are generally characterized by cohesive sediments colonized by aquatic vegetation. These regions with finer sediment deposits are associated with relatively high PCB concentrations, as discussed in Section 4.5.3.2. The River's sediments are much coarser within Reach 7 due to the relatively high current velocities, and become finer again within Rising Pond.

8.3.5.5 Floodplain Soils

In the proximal and distal floodplains, the presence of widespread vegetation generally minimizes erosion of soils during overbank flows. The stems of vegetation reduce bottom shear stresses while their roots inhibit erosion. Vegetation stems and leaves also act as filters for suspended sediment, thereby trapping fine-grained suspended solids during overbank flow periods. Therefore, PCBs and other hydrophobic constituents associated with suspended sediments entering the floodplain regions of the River will likely be deposited there.

8.3.5.6 Sediment Transport

Sediment transport between the Confluence and Woods Pond Dam is primarily affected by the following processes: resuspension, deposition, bed load, bank erosion, and watershed sediment loads. Resuspension and deposition processes impact suspended load transport in the River, with biotic solids, clay, silt, fine sand and medium sand being transported as suspended load; sediment particles with diameters less than 500 μm are generally found in the water column. Resuspension, or erosion, of bed sediment is controlled by bottom shear stress, sediment type (cohesive or non-cohesive), and various bed properties, including grain size distribution, dry density, state of consolidation, gas content, and mineralogy. Sediment deposition rate at a particular location is determined by local bottom shear stress, settling speed of depositing particles, and particle size distribution of suspended sediments. Bed load transport primarily affects coarser sediment (i.e., medium sand, coarse sand and gravel). Sediments moved by bed load typically roll or "saltate" along the bed in a thin layer that is typically about 10 particle diameters thick (van Rijn, 1984). Bank erosion acts as an additional sediment source to the River that generally occurs episodically during high-flow events. Sediment loads from tributaries and upstream sources are important because the magnitude and composition of these loads have a major impact on sediment transport processes in the River. Watershed sediment loads impact sedimentation rates in the River, which often have a primary effect on burial rates of PCBs from the bioavailable layer of the bed.

The impacts of these sediment transport processes on bed morphology in Reaches 5A and 5B were examined using channel cross-section data obtained by EPA between 1999 and 2002. Bed elevation and channel geometry data were collected along nine transects (i.e., channel cross-sections) located between the Confluence and New Lenox Road Bridge, as shown on Figure 8-3. Bed elevation at various points across the channel was measured at each transect location, at four different times: 1999, September 2001, April 2002, and June 2002.

These data are useful for evaluating changes in bed morphology at the nine transect locations between 1999 and 2002. Figure 8-4 shows changes in bed elevations during the nine-month period from September 2001 to June 2002. Net changes in bed morphology for the different transects and observation periods were quantified by calculating the average variation in bed elevation over the entire transect for a particular period (Table 8-2). The 1999 to June 2002 comparisons were only made for five transects; the 1999 data at the other four transects (49, 61, 192, and 198) could not be lined up with the more recent data with sufficient accuracy to provide meaningful results.

Table 8-2. Average Change in Bed Elevation at Nine Transects in Reaches 5A and 5B

Reach	Transect	Sept 2001 to April 2002 Change (ft)	April 2002 to June 2002 Change (ft)	Sept 2001 to June 2002 Change (ft)	1999 to June 2002 Change (ft)
5A	49	0.08	0.05	0.12	NA
	61	0.16	0.40	0.56	NA
	89	-0.27	-.024	-0.51	0.13
	133	-0.03	-0.18	-0.21	0.10
	153	0.75	0.33	0.42	-0.57
5B	198	0.40	-0.09	0.31	NA
	194	0.37	-0.16	0.22	-0.28
	192	0.16	-0.24	-0.07	NA
	182	0.01	-0.16	-0.15	2.67

Notes:

1. Positive change = net bed aggradation; negative change = net bed degradation.
2. NA = no analysis completed because 1999 transect could not be properly referenced.
3. Transects are listed in order moving from upstream to downstream.

Several observations concerning bed morphology in Reaches 5A and 5B may be made from the above analyses. First, significant bed aggradation or degradation (i.e., 1-2 feet) may occur at different locations along a particular transect during periods ranging from two months to nearly two years. Second, bed movement appears to generally be higher at the locations surveyed in Reach 5A (Figure 8-4a) than for those in Reach 5B (Figure 8-4b). Third, seven transects of the nine experienced net aggradation between September 2001 and April 2002, which was a period during which the peak daily average flow rate at the USGS Coltsville gage was 321 cfs. Net degradation occurred at six of the nine transects for the April 2002 to June 2002 period, when the peak flow was 618 cfs. Thus, increased bed degradation was observed during the higher-flow period (i.e., April to June), which would be expected. These results suggest that bed load may have a significant impact on bed morphology in Reaches 5A and 5B because the relatively large magnitudes of aggradation and degradation at some locations are unlikely to be caused solely by deposition or resuspension of suspended sediment. In order for sediment deposition and erosion to cause bed elevations changes of this magnitude, TSS levels observed in the water column would need to be much higher than the levels observed in the data.

8.4 Chemical Characteristics of the System that Affect Chemical Fate and Transport

Of the numerous system characteristics that affect chemical fate and transport, organic carbon is the most important for hydrophobic organic chemicals such as PCBs.

8.4.1 Impacts of Organic Carbon on Fate and Transport

Due to their low aqueous solubility and elevated octanol-water partition coefficients, PCBs and other hydrophobic organic compounds preferentially partition to organic carbon within natural aquatic systems. Therefore, to understand the fate of PCBs, it is first necessary to characterize the distribution of organic carbon in the system. Organic carbon appears both in particulate form (e.g., a portion of suspended matter) and in "dissolved" form (e.g., organic molecules such as humic acids), in both the water column and sediment bed. Particulate-phase sediment PCB concentrations are generally positively correlated to organic carbon concentration (i.e., higher PCB concentrations are generally observed in areas having fine-grained, high organic carbon sediments). Consequently, the fate of PCBs and other hydrophobic organic chemicals is bound to the fate of organic solids.

Dissolved forms of organic carbon can elevate the dissolved-phase concentrations of PCBs and other hydrophobic compounds. In sediments, these elevated concentrations produce elevated pore water chemical concentrations, which in turn promote higher dissolved chemical fluxes between sediments and overlying waters. Autochthonous generation of water column organic solids such as phytoplankton impacts hydrophobic organic chemical dynamics. Dissolved-phase chemicals partition onto organic solid particles. Chemical fate is then coupled with the fate of water column organics and subject to downstream transport processes, bioaccumulation within the food chain, and settling to the sediment bed.

8.4.2 Water Column Organic Carbon

The amount of PCBs that sorb to water column particulates is proportional to the particulates' organic matter content, which is quantified as the fraction of organic carbon (f_{oc}). Figure 8-5 contains a temporal profile of water column f_{oc} at five locations within Reaches 5, 6, and 8: 1) Dawes/Pomeroy Avenue; 2) New Lenox Road; 3) Woods Pond Headwaters; 4) Schweitzer/Lenoxdale Bridge; and 5) Division Street.

Figure 8-5 illustrates that measured f_{oc} ranges between approximately 1% and 30% at each location, with some limited evidence of seasonality. A seasonal trend characterized by higher f_{oc} in the summer would be expected in regions where algal growth is significant. As shown on Figure 8-5, despite the year-to-year variability, the data from Woods Pond Headwaters contain the most distinct seasonality of all stations, which is consistent with visual observations and other data that indicate significant primary production of algal and macrophyte growth in this region of the River. It would therefore be expected that a higher fraction of PCBs would be sorbed to water column suspended matter at the locations and times when the f_{oc} is high (e.g., at Woods Pond during the summer months).

As stated above, in addition to being bound to sediment particles, organic carbon is also present in the water column in dissolved form. Figure 8-6 shows temporal and spatial profiles of 1998-1999 EPA water column data on DOC collected between Dawes/Pomeroy Avenue and Schweitzer/Lenoxdale Bridge. The average DOC concentration is approximately 5 mg/L; the data exhibit no clear spatial trend. Assessment of temporal trends is difficult given the limited dataset (i.e., a single year). These DOC concentrations are consistent with those observed in other similar systems (e.g., Wetzel, 2001), and are indicative of refractory (i.e., slowly degraded) carbon moving through the system. Because of the relatively low DOC concentration and the higher affinity of PCBs for POC, the fraction sorbed to DOC in the water column is likely low in comparison to that sorbed to POC.

8.4.3 Sediment Organic Carbon

Organic carbon is the primary sorption site for PCBs in the sediments; the mass of PCBs sorbed is generally dependent on the amount of organic carbon. As discussed in Section 4.4.1, average surface sediment f_{oc} in Reaches 5 and 6 increases with distance downstream, from approximately 1.5% in Reaches 5A and 5B to 2.6% in Reach 5C, and then increases substantially to approximately 9-10% in the backwaters upstream of Woods Pond and in Woods Pond (Figure 4-3). This spatial pattern in sediment organic carbon is consistent with the observed increase in biological productivity (e.g., algae, submerged aquatic vegetation, and macrophytes) primarily in the backwaters and Woods Pond, which is linked to the nutrient inputs from the WWTP, as well as the decreased gradient in these areas (Section 2). Annual decay of this material is a continuous source of organic carbon to surface sediments. In several areas of the river that are highly depositional (e.g., Reach 5C, backwaters, Woods Pond), sediment f_{oc} is generally higher in surface sediments (top 6 inches) as compared to deeper sediments (e.g., Figure 4-10). This difference may be explained by deposition of organic matter to the surface sediments (e.g., dead algae), followed by subsequent decomposition that occurs at depth in the bed. Downstream of Woods Pond Dam, f_{oc} is generally lower in the free-flowing portions of the River (i.e., Reaches 7 and 9), and is higher on average within the impoundments, particularly behind Glendale Dam and within Rising Pond (e.g., Figure 4-2). These differences in organic carbon distribution appear to affect, in part, the distribution of PCBs (see Section 4.5.3.1).

DOC in sediment pore water can be a significant sorbant of chemicals that are highly hydrophobic, thereby increasing the fraction of PCBs that can be transported to the surface water in the dissolved phase. As part of the 2001 EPA/GE partitioning study, DOC was measured in sediment pore water. Figure 8-7 depicts the spatial profile of pore water DOC between the Confluence and Woods Pond. Based on this plot, there is no apparent spatial trend in the data, with an average pore water DOC concentration for Reaches 5 and 6 of approximately 16 mg/L. This concentration is about three times higher than that observed in the water column. Consequently, sorption of PCBs to pore water DOC may be important.

8.5 Biological Characteristics of the System that Affect Chemical Fate, Transport, and Bioaccumulation

The pathways by which PCBs are transferred through the aquatic food web are controlled by fish movement patterns and the structure of the food web.

8.5.1 Movement Patterns/Exposure Areas

Understanding the regions of the River over which individual fish are exposed to PCBs is an important part of assessing PCB bioaccumulation patterns. As described in Section 2, the character of the River changes dramatically near the WWTP outfall. Above the WWTP, the River is relatively shallow, fast-flowing, and characterized by coarser sediments and no significant backwaters. In addition, algal biomass and invertebrate abundances are lower upstream of the WWTP. Downstream from this point, the River changes, being characterized by deeper water, finer sediments, and by the increasing area of shallow backwater habitats towards Woods Pond.

These changes in river character have consequences for the biology of the system. Increasing habitat diversity, finer organic-rich sediments, and greater algal and plant biomass in Reaches 5B, 5C, and 6 affect sources of food to the fish and possibly contaminant exposure routes. With respect to the fish fauna, the cyprinids, such as the dace, darters, and minnows, are common in the East and West Branches and in the upstream portion of Reach 5, above New Lenox Road Bridge, but become less common downstream in Reach 5C and Woods Pond (Chadwick and Associates, 1994; R2, 2002). The cyprinids are also common in the brooks (Moorewood, Sackett, Mill, Felton, and Roaring Brooks) that are tributaries to Reach 5, as is brown trout (R2, 2002). The centrachids (e.g., the sunfish and largemouth bass), yellow perch, white sucker and brown bullhead are more abundant in the slower, deeper sections, Reaches 5C and Woods Pond (Chadwick and Associates, 1994; R2, 2002).

PCB concentrations in the media to which fish are exposed vary over the reach from the Confluence to Woods Pond Dam (Reaches 5 and 6). Organic carbon-normalized PCB concentrations in the surface sediments (which represent the sediment-based portion of food-web exposures for fish) decline at least 10-fold from the Confluence to the WWTP, and then exhibit no consistent trend to Woods Pond Dam (e.g., Figure 4-12). In contrast, average water column PCB concentrations increase approximately 40% over Reach 5A, are similar in Reaches 5B and 5C, and then decline over Reach 6 (Woods Pond) by less than a factor of two (e.g., Figure 3-7). Where PCB concentration gradients exist, the extent to which fish move across those gradients or remain in a small home range may be reflected in the spatial trends in fish tissue PCB concentration for a given species. Hence, spatial gradients in fish PCB concentrations that mimic gradients in sediment or water provide evidence of limited movement through the River reach.

Fish tissue PCB concentrations show no clear trends among Reaches 5A, 5B, 5C and 6 that are consistent across species. This is true both on a reach-average basis (Section 6.3.3) and on a finer spatial scale (Figure 8-8). It is also true whether the data are viewed on a wet-weight or a lipid-normalized basis (see Section 6.3.3). Thus, downstream of the WWTP, over Reaches 5B, 5C, and 6, sediment, water and fish data are generally consistent with one another. For example, in Reaches 5B and 5C, where there are multiple fish sampling locations, there are no strong gradients in either organic carbon-normalized sediment or water column PCB concentrations and no apparent gradients in fish tissue PCB concentrations (Figure 8-8). In contrast, in Reach 5A, organic carbon-normalized surface sediment PCB concentrations decline, water column PCB concentrations increase, and fish PCB concentrations exhibit no consistent pattern.

There are several potential explanations for this lack of consistent gradients in Reach 5A. First, the fish may move extensively over this region of the River such that their exposure is not tied directly to local surface sediment or water column concentrations. Second, variability in the data may mask spatial gradients. Very few fish were collected in Reach 5A, and in general in the Housatonic River dataset, variability is relatively large (see, e.g., Figure 8-8). However, this is at best a partial explanation, since the variations in fish PCB concentrations are considerably less than the 10-fold decline in surface sediment organic carbon-normalized PCB concentrations. Third, diets may change over this reach of the River. Shifts in exposure resulting from shifts in the relative importance of sediment- and water column-based sources of food are explored in Section 8.8.4.

8.5.2 Food Web Structure

Understanding the fate of PCBs in fish requires an understanding of the various exposure routes and pathways through the riverine food web. The PCBs accumulated by fish come from both the water column and the sediment. The relative importance of these two PCB sources depends upon their relative PCB concentrations and also upon the structure of the food web itself.

A simplified food web of the Housatonic River, which contains primary producers, invertebrates, and fish, is presented on Figure 8-9.

Primary Producers

Phytoplankton, periphyton, and macrophytes form the base of the aquatic food web. These autochthonous sources of organic matter are supplemented by allochthonous organic matter derived from terrestrial plants that enters the River through run-off from the surrounding watershed. Water column dissolved PCBs sorb to organic matter contributed by both of these sources. Plant production, senescence, and settling provide a sink for water column PCBs and a source of PCBs to the sediments. The importance of this mechanism is directly related to the growth and settling rates of phytoplankton. Water column and benthic invertebrates consume both living and non-living organic matter, and thus are the first step in the bioaccumulation of PCBs within the aquatic food web. The relative importance of plant production to PCB fate, transport, and bioaccumulation can be assessed by examining patterns in organic matter, nutrient, and phytoplankton (as indicated by chlorophyll-*a*) concentrations measured in surface water samples.

The most common limitation to algal growth within a river is the availability of nutrients, with phosphorus almost always being the limiting nutrient element, although light can be a limiting factor under some conditions. Nutrient limitations to phytoplankton growth occur at about 5 to 25 µgP/L (measured as orthophosphate or soluble reactive phosphorus [SRP]) and 25 to 100 µgN/L (measured as the sum of ammonia and nitrate) (Chapra, 1997). Based on the 1998-1999 EPA routine monthly water column sampling data, the primary limiting factor to growth between the Confluence and the Pittsfield WWTP appears to be nutrients, as indicated by the nitrogen and phosphorus data plotted on Figure 8-10. Because the measured SRP in Reach 5A is below these limiting values, phytoplankton growth is likely to be phosphorus-limited. Chlorophyll-*a* concentrations of about 2 µg/L indicate that phytoplankton biomass in Reach 5A is relatively low level (Figure 8-10). At the location of the WWTP discharge, the data indicate a significant increase in nutrient concentrations, which promotes increased phytoplankton growth (Figure 8-10). Chlorophyll-*a* concentrations, however, typically remain low in Reaches 5B and 5C, with mean values of 2 µg/L to 3 µg/L, due to the relatively short residence time in this flowing system. At Woods Pond, the residence times increase and phytoplankton concentrations concomitantly increase, as evidenced by the increase in chlorophyll-*a* concentrations (Figure 8-10). The increased hydraulic residence time and productivity in Woods Pond allow for increased settling of phytoplankton. Hence, it is in Woods Pond that the most significant impact of phytoplankton on PCB transport is expected to occur. The average 1998-1999 chlorophyll-*a* concentrations in Woods Pond (i.e., 5-10 µg/L) are not at levels that are typically associated with a highly productive system. However, visual observations at this location during summer months have indicated the presence of significant populations of macrophyte beds and standing mats of algae, both of which would affect PCB transport as described above, but would not be captured by a grab sample of water flowing past the Woods Pond outlet because water column sampling has not been performed within the Pond itself. Temporal trends in chlorophyll-*a* from the Woods Pond region also exhibit seasonal trends indicative of algal growth within the Pond (Figure 8-11).

The relative importance of phytoplankton carbon as a factor influencing PCB dynamics can be further evaluated by comparing the estimated phytoplankton carbon standing crop with total organic carbon in the River. Based on the data plotted on Figure 8-10, phytoplankton biomass above the WWTP is approximately 0.08 mgC/L (assuming a carbon to chlorophyll ratio of 40) (Chapra, 1997). This estimate is consistent with POC concentrations measured in phytoplankton samples collected during EPA's phytoplankton biomass study (Weston 2002). Average POC concentrations in this portion of the River are approximately 0.5 mgC/L. Thus, phytoplankton biomass likely represents less than 20% of the POC in Reach 5A. Phytoplankton production, therefore, is not likely to be a significant factor in the dynamics of PCBs in Reach 5A. Using a similar calculation, phytoplankton carbon concentrations downstream of the WWTP of approximately 0.1 mg/L represent 20% to 40% of the total POC in Reaches 5B and 5C. In Woods Pond, phytoplankton biomass is approximately 0.2 mgC/L to 0.4 mgC/L. Although they may not be representative of the more stagnant portions of the Pond, POC values from Schweitzer Bridge average 0.4 mgC/L. Based on these data, phytoplankton may represent a significant fraction of the total POC, and therefore may contribute significantly to the PCB dynamics within Woods Pond.

Further indication of the degree of primary production within Reach 5C and Woods Pond is provided by the macrophyte biomass survey performed by EPA in September 2000 (Weston 2002). Within each subreach between the Confluence and Woods Pond Dam, three plots were harvested for macrophyte tissue; the average dry weight tissue density is listed in Table 8-3 (below).

Table 8-3. Macrophyte Density and Areal Coverage

Reach	Average Macrophyte Density (g/m^2)	Percent Surface Area Containing Macrophytes (including backwater regions)
5A	24	1%
5B	186	25%
5C	334	57%
6	140	55%

Note:
g/m^2 = grams per square meter

Similar to the spatial trend in phytoplankton, the values in this table indicate an increase in macrophyte density downstream of the WWTP (i.e., below Reach 5A). The average densities in Reach 5C and Woods Pond and its backwaters (i.e., 200 grams per square meter [g/m^2] to 300 g/m^2) are considered moderate to high for a riverine system (Wetzel, 2001; Stevenson, 1988), and further illustrate the high productivity in this reach. Estimates of areal macrophyte coverage reported by EPA (Weston, 2002) were normalized by the reach-wide total surface area and are listed in Table 8-3. These values demonstrate the relatively large areal extent of macrophyte populations in Reach 5C and Woods Pond.

Macrophytes also provide surface area for the growth of periphyton, which accumulate PCBs from the water column and serve as food for invertebrates. Measurements of periphyton biomass made on EPA's behalf indicated that periphyton attached to macrophytes were much more abundant in Reaches 5C and Woods Pond than in Reaches 5A and 5B (Weston, 2002). Furthermore, macrophytes themselves sorb PCBs and their senescence provides another route for PCB transfer to the sediment bed. As the plant material decomposes and is consumed by benthic invertebrates, PCBs originally sorbed from the water column can enter the food web.

Invertebrates

Components of the invertebrate fauna significant to the trophic transfer of PCBs to fish include zooplankton, insect larvae, worms, and crayfish. Sampling conducted by EPA within Reach 5 indicate that the abundance of benthic invertebrates increases towards Woods Pond (Figure 8-12), which is consistent with the change in River bed characteristics over this reach. Finer sediments accumulate in the bottom in this area (i.e., Reaches 5C and 6), as the River deepens and slows. The higher organic carbon content of these sediments serves as a food supply for the invertebrates

Fish

Forty-one species of fish have been documented from the Massachusetts reaches of the Housatonic River and adjacent ponds (Chadwick and Associates, 1994; R2, 2002). These are shown on Figure 8-13 by their trophic level (TL) positions, depending on whether they prefer water-column invertebrate prey, benthic prey (i.e., they feed along the bottom and/or in the bottom sediments), or are predatory on other fish species. In a September 1993 survey, white sucker, sunfish (pumpkinseed and bluegill), yellow perch, brown bullhead, and largemouth bass were the most abundant species between the Confluence and Woods Pond Dam (Chadwick and Associates, 1994). In recent surveys conducted in 2000 and 2001 upstream of Woods Pond Dam, 26 of the species listed on Figure 8-13 were found (R2, 2002). The top five most abundant species caught during an October 2001 survey in the main channel of the River were yellow perch, largemouth bass, sunfish (including pumpkinseed, bluegill, and juvenile sunfish), black crappie, and rock bass (R2, 2002).

8.6 Sources of PCBs and PCDDs/PCDFs to the System

Assessment of chemical fate and transport necessitates the quantification of contemporary sources to the system. For the purposes of this discussion, the Rest of River system is defined as the water and sediments within the main channel, backwater regions, and floodplains, as well as the biota living in or feeding from these areas. External sources would therefore consist of inputs from tributaries, groundwater, manmade discharges, and the atmosphere (via non-point sources such as direct runoff).

This discussion of sources, as well as the subsequent discussions of fate and transport mechanisms, focuses on PCBs and, to a lesser extent, PCDDs/PCDFs (see Section 2.6).

8.6.1 PCBs

8.6.1.1 Upstream of Confluence

As discussed in Section 2, the Consent Decree defines the upstream boundary of the Rest of River as the Confluence of the East and West Branches. The PCB load entering the Rest of River at this point represents the most significant external source of PCBs to the system; PCB sources associated with the two branches are discussed separately below.

<u>East Branch</u>

Historically, the vast majority of the PCBs entering the Rest of River system has originated from the East Branch. PCB loadings transported to the system in the East Branch originated from the GE Pittsfield Plant area via a number of sources, including:

- Surface water runoff and discharges, including Unkamet Brook and Silver Lake;
- Groundwater flow, including migration of PCBs in LNAPL and DNAPL forms to some extent; and
- Transport of PCBs from the sediments, and potentially bank soils to some extent, within the reach above the Confluence via diffusion, erosion, and bed load transport.

The external sources to the East Branch of the River (e.g., groundwater and NAPL) have been controlled by on-site mitigation measures, as discussed in Section 1.4.1. Further, the water column PCB mass transport in the East Branch at Dawes/Pomeroy Avenue over the last several years is consistent with that which would be expected based on the sediment PCB concentrations measured upstream of the Confluence in recent years. Therefore, the PCB-containing sediments have likely been the most significant contributor to PCB loads upstream of the Confluence in recent years. Remediation activities to address the sediments in these areas have been completed in the Upper ½-Mile Reach and are underway in the 1½-Mile Reach.

Data from the Dawes/Pomeroy Avenue monitoring stations were used to represent PCB loads entering the Rest of River system from the East Branch. As discussed in Section 3, PCB concentrations within the system differ significantly between flows above and below 100 cfs (at Coltsville), due primarily to increased transport of sediments and associated PCBs during higher flows. Based on the 1996-2002 data, the average water column PCB concentrations at the Dawes/Pomeroy locations are approximately 0.06 µg/L at the lower flows and 0.08 µg/L at the higher flows, with fairly large year-to-year differences (see Section 3, esp. Figure 3-10). For the 1997-2002 period (see Section 8.8.1.1), the average PCB loading at this location was calculated to be approximately 7 grams per day (g/d) at the lower flows and 81 g/d at the higher flows. Integrating these loadings on an annual average basis through flow-weighted averaging yields a mean PCB loading at this location of approximately 28 g/day, or 10 kilograms per year (kg/yr). It is anticipated that this load will decrease due the effects of the sediment remediation in the Upper ½-Mile and 1½-Mile Reaches. Water column PCB loads in the system are discussed in more detail in Section 8.8.1.

<u>West Branch</u>

As discussed in Section 3, water column sampling from the West Branch has not been conducted routinely. However, the limited data from samples collected just above the Confluence do indicate that PCBs have been detected at this location. The source of these PCBs is likely sediments within the West Branch, which contain PCBs in some isolated regions (e.g., PCBs were detected in about half of the 36 surface sediment samples collected by EPA in 1999 from the West Branch within 1 kilometer [km] of the Confluence, with all but two detected concentrations being near or below 1 mg/kg).

Since 1998, 40% of the water column samples collected from the West Branch have yielded detectable PCBs; concentrations are typically much lower than those in the East Branch. Depending on the assumptions made for non-detect samples, average water column PCB concentrations in the West Branch range from approximately 0.015 μg/L to 0.025 μg/L (Figure 8-14), which is at the lower end of the typical detectable range. Although the data are not sufficient to support an accurate calculation of PCB loading, a gross estimate can be obtained by multiplying the concentrations by daily average flow rates estimated from measured flow at Coltsville and drainage area proration (Appendix E.1). This approach yields a low-flow average load from the West Branch of about 2 g/d and a high-flow mean of 10 g/d to 16 g/d, producing a flow-weighted average of about 4 g/d to 6 g/d, or 2 kg/yr.

Thus, the current primary source of PCBs entering the Rest of River system from upstream is the East Branch, with inputs from the West Branch being measurable but much less significant. The PCB loadings discussed above will be compared against estimates of PCB loads associated with various fate and transport mechanisms within the system in Section 8.8.

8.6.1.2 Tributaries Downstream of the Confluence

As discussed in Section 2, there are a few small tributaries in Reach 5 (Sackett Brook, Roaring Brook, and Yokun Brook). The tributaries to Reaches 7 through 9 are larger and include Hop Brook and the Williams, Green, and Konkapot Rivers, plus those in the Connecticut portion of the River. There are no recent sampling data to assess inputs of PCBs from these tributaries. Based on review of spatial trends in water column and sediment PCB data, primarily within Reaches 5 through 8, there are no data that would suggest that PCBs are entering the system from tributaries. Therefore, tributaries do not likely represent a significant contemporary source of PCBs to the system. One exception may be the Still River, Connecticut, where previous studies have documented some evidence of PCBs in the sediments and biota (e.g., Frink et al., 1982; BBL, 1996). However, the data in this portion of the Housatonic River are insufficient to assess the current impacts of this potential source.

8.6.1.3 Point Sources

A number of permitted discharges within the Rest of River system could be classified as potential point sources. These include the discharge from the Pittsfield WWTP in Reach 5, paper mills in Lee and South Lee, and municipal wastewater treatment plants in Lee and Great Barrington, all of which discharge to the River in Reach 7 (EPA, 2002). There are also several municipal and some industrial discharges within the Connecticut portion of the River. The flow inputs from most of these facilities are relatively small compared to the flow within the River, and PCBs are not measured in their effluent. Further, based on review of spatial trends in water column and sediment PCB data, primarily within Reaches 5-8, there are no data that would suggest that PCBs are entering the system from these discharges. Therefore, point source discharges within the Rest of River are likely not a significant contemporary source of PCBs to the system.

8.6.1.4 Groundwater

Previous studies of groundwater within the Housatonic River and its surrounding area were mainly focused on the GE Pittsfield Plant area, where PCB contamination in local groundwater has been identified and control measures have been implemented in some areas (e.g., BBL, 2000a). Little data exist to evaluate groundwater interactions with the River downstream of the Confluence. Previous studies have indicated that the River serves as a net discharge zone for regional overburden groundwater, with the exception of areas near the dams, where the River loses water to the subsurface (BBL, 1996; ChemRisk, 1996). As discussed in Section 2, however, the River is predominately fed by precipitation runoff; flow from groundwater is a very minor component of the system water budget. Impacts on the River from PCBs in groundwater in the GE Plant reach have been documented in the past, but these were impacted by local LNAPL and DNAPL plumes (BBL, 2000a). There are no data or information that indicate PCB contamination of groundwater within the Rest of River reach. Further, review of spatial trends in water column and sediment PCB data does not suggest the presence of any regions in the Rest of River in which PCBs are entering the system from groundwater. Therefore, groundwater is likely not a significant contemporary source of PCBs to the Rest of River system.

8.6.1.5 Atmospheric Deposition

Due to their wide-scale use in the past and their high affinity for particulate matter, PCBs have been found to be ubiquitous within the environment. Therefore, atmospheric sources can result in a net flux of PCBs to a watershed through both dry deposition processes and precipitation. Atmospheric sources of PCBs, however, are usually only significant to water bodies with large watersheds and large surface areas. There have been no studies that have attempted to directly measure atmospheric fluxes of PCBs in the Housatonic River watershed. Results reported by the Integrated Atmospheric Deposition Network (IADN) indicate that the maximum atmospheric deposition measured at various stations in the Great Lakes during 1997-1998 was 0.011 $\mu g/m^2/day$ (IADN, 1998). Applying this flux to the surface area of the River within Reaches 5 and 6, including backwaters, translates into an annual PCB load of less than 0.01 kg/yr, which is less than 0.1% of the mass entering the Rest of River from the East Branch. This calculation suggests that atmospheric deposition is not a significant source of PCBs to the Rest of River system.

8.6.2 Sources of PCDDs/PCDFs

Since summary information on PCDDs/PCDFs is included in the discussions of the various media in this RFI Report (for the reasons given in Section 2.6), a brief discussion of potential sources of these compounds is presented here. Due to the hydrophobic nature of PCDDs/PCDFs, sediments provide a record of past source activity. While such records are modified by fate and transport processes, they are the most reliable data upon which to infer source activity. Therefore, the discussion of PCDD/PCDF sources in this section focuses on sediment data. Water column monitoring for PCDDs/PCDFs at the site was not sufficient to permit credible estimates of sources and associated loadings.

8.6.2.1 Spatial Patterns and Potential Sources

As discussed in prior reports (e.g., BBL, 1996; Eitzer, 1993) and shown by the PCDD/PCDF data included in the GE and EPA databases (Appendix F), PCDDs/PCDFs have been detected in sediment samples collected both adjacent to the GE facility and upstream of Pittsfield. These data indicate that the East Branch is a source of PCDDs/PCDFs to the Rest of River. The fact that PCDDs/PCDFs were detected in sediments both upstream and adjacent to the GE facility implies that PCDDs/PCDFs entering the Rest of River and measured in downstream sediments may originate from multiple sources upstream of the Confluence.

Sediment PCDD/PCDF data from all depths collected in Reaches 5 through 8 are plotted spatially on Figure 8-15. The analytical method used to measure PCDDs/PCDFs quantifies the concentration of seventeen congeners and eight homolog groups. The various congeners and homologs exhibited similar trends; therefore data from only one representative PCDD and PCDF congener and homolog group each are plotted on Figure 8-15.

Despite significant variability (e.g., concentrations often range over two or more orders of magnitude over short distances), the spatial trends in the PCDD/PCDF data contain several features. These features are most clearly observable when the concentrations are plotted on a reach-averaged basis (Figure 8-16). For the purposes of this analysis, the data were averaged by reach (Reaches 5A, 5B, 5C, 6, and 8) based upon the location of potential sources, spatial differences in River channel and sediment characteristics, patterns of historical sediment PCB concentrations, and data coverage.

In general, PCDD/PCDF concentrations increase over the reach between the Confluence and Woods Pond (Figures 8-15 and 8-16). The patterns evident on Figure 8-16 indicate that concentrations of some PCDD/PCDF congeners and homologs are lower in Reach 5B than in Reach 5A, and then increase in Reach 5C, which is likely due to the higher concentration of organic carbon contained in the sediments; this trend was also observed in the PCB data (Section 4.5). Higher concentrations of both PCDDs and PCDFs are observed in Woods Pond (Reach 6) and Rising Pond (Reach 8). These results are consistent with known sediment deposition patterns within the system (i.e., low-energy environment within the impoundments), as inputs of hydrophobic constituents from sources located upstream tend to accumulate with the fine, high organic content sediments in these downstream impoundments. However, the PCB data presented in Section 4 indicate that PCB concentrations in Rising Pond are much lower than those in Woods Pond (due to a reduction in PCB transport and dilution from clean solids that enter the River over the 20-mile reach between these impoundments), whereas the PCDD/PCDF data indicate the opposite (Figures 8-15 and 8-16). The presence of higher PCDD/PCDF concentrations in Rising Pond sediments relative to Woods Pond may suggest additional sources within this reach of the River.

8.6.2.2 Composition Trends

Observed changes in composition across the four reaches were used to further evaluate potential sources of PCDDs/PCDFs to the River. Reach-averaged PCDD/PCDF homolog weight percents are plotted on Figure 8-17. As stated above, average PCDD/PCDF concentrations generally increase with distance downstream across the reaches between the Confluence and Woods Pond Dam (Figure 8-16). This increase is likely a result of the increased accumulation of fine-grained, organic-rich sediments (to which hydrophobic organic chemicals preferentially sorb). However, composition in these reaches is relatively similar, characterized primarily by a significant fraction of OCDD (D8) (approximately 37% to 43%; Figure 8-17). The patterns on Figure 8-17 indicate that a shift in the average homolog composition is observed in Rising Pond (Reach 8). In this reach, not only are average PCDD/PCDF concentrations higher than in Woods Pond but the composition contains a higher proportion of the heptachlorodibenzo-p-dioxin (HPCDD) and OCDD compounds, which again may suggest additional PCDD sources between Woods Pond and Rising Pond. The presence of paper mills at Columbia Mill and Willow Mill Dams and the strong D7-D8 signal in the Rising Pond composition are consistent with this suggestion.

8.6.2.3 PCDD/PCDF TEQs

As discussed in Section 4.9, another method of assessing PCDD/PCDF sources is by calculating the total TEQ concentrations for the PCDD/PCDF compounds in the samples. These TEQ values are plotted in the top panel of Figure 8-18. The spatial pattern in this plot generally follows that of the individual congeners and homologs discussed above. TEQs calculated for samples collected in Reach 5 exhibit a large amount of variability, but are generally within the 10-100 pg/g range. Relatively higher TEQs occur in the Woods Pond and Rising Pond sediment data, due to the higher PCDD/PCDF concentrations associated with the high inventory of organic carbon in these impoundments.

The calculated TEQs were averaged for the same four reaches described above, and are plotted in the bottom panel of Figure 8-18. Since the data analyses described above suggest there may be additional sources of PCDDs between Reaches 6 and 8, the reach-average TEQs were proportioned among the PCDD and PCDF compounds in this plot. Differences in this proportion among the reaches may be indicative of different sources. Reach-average TEQ concentrations range from approximately 40 pg/g in Reach 5A to approximately 200 pg/g in Reach 6 (Woods Pond). However the PCDD fraction of the TEQ is relatively constant, at approximately 20%. Conversely, nearly 30% of the 175 pg/g average TEQ in Rising Pond is associated with PCDDs. This shift further implies that there may be an additional source of PCDDs downstream of Woods Pond, which is consistent with the observed patters in PCDD/PCDF concentrations and composition discussed above.

8.7 PCB Composition in the System

The fate of PCBs in the system is affected by PCB composition. A number of physicochemical and biochemical processes ultimately depend on PCB composition (e.g., partitioning, volatilization, and bioaccumulation). As discussed in Sections 3 and 4, the majority of PCBs detected in the Housatonic River water column and sediment were quantified as Aroclor 1260 and, to a lesser extent, Aroclor 1254. These quantifications are consistent with the source Aroclors used at the GE Pittsfield facility. These compounds are towards the heavier end of the PCB spectrum, with the majority of the PCB congeners having between five and seven CL/BP. Higher chlorinated congeners are generally less soluble in water and tend to bioaccumulate more readily as they have a higher affinity for lipids. Also, the extent to which PCBs sorb to organic matter generally increases with increasing number of CL/BP. Therefore, an understanding of PCB composition, and how such composition changes in the system, is important in the evaluation of PCB fate and transport. The majority of Housatonic River water column, sediment, and fish data collected since 1980 have been quantified as Aroclor PCBs. However, more recent data collection efforts by EPA have also quantified PCBs at the congener-specific level; these congener-specific data were used to evaluate PCB homolog composition in Sections 3 through 6.

The homolog distributions are generally consistent with the Aroclor quantifications (i.e., predominance of Aroclor 1260, with a lesser amount of Aroclor 1254). However, they do show some slight differences among media and reaches. As discussed in Section 4.8, PCBs in the sediments consist predominantly of congeners with six (hexa) or seven (hepta) CL/BP. A slight increase in less chlorinated congeners occurs near Woods Pond, which may be the result of modest dechlorination processes (see Section 8.8.1.11). In general, the water column PCB composition has a greater percentage of lower chlorinated congeners than is observed in the sediment (e.g., Figure 3-20). This same shift in composition between the water column and sediment data is consistent with the observed shift in the average Aroclor 1254 and 1260 quantitation shown in Tables 3-12 and 4-11. Further, the PCB composition observed in dissolved water column samples (Figure 3-20) is consistent with that expected from diffusion of lighter chlorinated PCBs from sediment pore water during low-flow conditions (Figure 4-28). The propensity for desorption of lower chlorinated PCBs from sediments may be the cause of this shift in composition. In general, fish tissue homolog patterns are consistent with those observed in the water column and sediment data (e.g., Figure 6-11).

8.8 Mechanisms of PCB Fate, Transport, and Bioaccumulation

In this section, various mechanisms of PCB fate, transport, and bioaccumulation are discussed. Because of differences for some fate and transport mechanisms, the three hydrologic regimes in the system – main channel, backwaters, and floodplains – are discussed separately. For each regime, the important mechanisms are discussed, and to the extent possible, data analyses and calculations are presented to evaluate their relative importance. This section focuses largely on Reaches 5 and 6, with some discussion of further downstream reaches as appropriate.

8.8.1 Main Channel

The major processes potentially affecting fate and transport of PCBs within the water column and sediments of the main channel in the system include:

- Water column transport (i.e., advection and dispersion);
- Partitioning of PCBs between particulate and dissolved phases;
- Diffusive exchange at the sediment-water interface;
- Deposition and resuspension, which contribute to sedimentation;
- Transport with bed load at the sediment-water interface;
- Exchange at the air-water interface (i.e., volatilization); and
- Transformations within the bed from reductive dechlorination.

8.8.1.1 Advection/Dispersion

Mass transport of constituents suspended and/or dissolved in the water column (e.g., solids and PCBs) is controlled by advective and dispersive processes in a river. Advection of water column constituents is caused by moving water, which is quantified by current velocity and flow rate. Current velocity is spatially and temporally variable; velocity at a particular location in a river depends upon different factors including channel gradient, bathymetry and channel geometry, bed roughness, vegetation, and flow rate. Dispersion in a river refers to mixing processes caused by turbulent fluctuations of the currents. Similar to other rivers, vertical turbulent mixing in the Housatonic River is in most places large enough to keep the water column well mixed under most conditions. Horizontal turbulent mixing processes vary in space and time, with horizontal dispersion generally increasing as flow rate increases in a river.

Mass transport of PCBs and other water column constituents can be separated into two broad categories: 1) in-channel flow conditions; and 2) overbank flow conditions. Flow in the River is confined within the main channel for in-channel conditions. The primary advective process is typically transport by currents along the longitudinal axis of the River channel. Lateral current velocities are generally significantly smaller than longitudinal velocities; lateral currents, however, make important contributions to horizontal mixing. Within the Rest of River system, mass transport between the main channel and adjoining backwaters is usually relatively small for in-channel flow conditions. Overbank flow allows PCBs and other constituents to be transported to the floodplain and backwaters during high-flow events. The magnitudes of advective and dispersive mass transport to the floodplain are spatially and temporally variable between the Confluence and Woods Pond. Local bathymetry and geometry conditions, along with the magnitude of the flood and position on the flood hydrograph, affect mass transport processes among the main channel, backwaters and the floodplain during overbank flow.

To evaluate PCB mass transport within the system, spatial patterns of in-River PCB loadings have been evaluated. These loadings quantify advective PCB transport; the spatial trends can be used to evaluate contributing mechanisms. Spatial profiles of average water column PCB loadings are shown on Figure 8-19 for each individual year from 1996 to 2002. Based on the observed dependence of PCB concentrations on flow (see Section 3), average loadings were separated into low flow and higher flow (i.e., below and above 100 cfs at Coltsville) in this plot. These plots indicate year-to-year differences in PCB loadings. Some of the variability in higher-flow loadings is related to flow. For example, the elevated loadings observed in 1999 can be explained by higher average flows during the days of sampling for that year (Figure 8-19b). The spatial trend and magnitude of the PCB loading during lower flows is generally consistent between 1997 and 2002, but the calculated low-flow loadings for 1996 are substantially higher. For example, at the first water column sampling location in Reach 5A (Holmes Road), the 1996 low-flow PCB loading is higher than the other years' averages at any of the remaining locations between 1997 and 2002. Further, there is much greater variability in the low-flow averages for the downstream sampling locations in 1996 (i.e., New Lenox Road, Woods Pond Headwaters). One possible explanation for the observed differences in PCB loading during 1996 may be due to changes in sampling and analytical methods that were implemented beginning in 1997. Consistent sampling and analytical techniques have been used by GE since 1997 which may explain the similarity in the data collected since that time. For these reasons, the analysis of spatial patterns in water column PCB loads presented in the remainder of this section focus primarily on the 1997-2002 GE data set. For completeness, these GE data were supplemented with the 1998-1999 EPA routine water column monitoring data.

Based on these data, average spatial profiles of advective PCB loads between the Dawes/Pomeroy Avenue and the Schweitzer/Lenoxdale Bridge, for flows both less than and greater than 100 cfs at Coltsville, are plotted on Figure 8-20. Under low-flow conditions (flows less than 100 cfs at Coltsville), there is a consistent increase in the average water column PCB load from approximately 7 g/d at Dawes/Pomeroy Avenue to approximately 22 g/d at Woods Pond Headwaters. The PCB load is transported downstream via advection, where it then decreases to approximately 18 g/d across Woods Pond. This decrease in loading is likely due to sorption of PCBs to abundant biotic solids present in Woods Pond that subsequently settle out of the water column (discussed further in Section 8.8.1.7). Low-flow PCB loadings downstream of Reach 8 (Rising Pond) measured at Division Street (not plotted) are lower, averaging 14 g/d; this decrease indicates PCB loss processes (e.g., volatilization and/or deposition) are occurring over this 20-mile stretch of the River.

Under higher-flow conditions (greater than 100 cfs at Coltsville), there is a notable difference in the spatial profile of water column loading (Figure 8-20). In general, PCB loadings under these flow conditions are nearly an order of magnitude higher than low-flow loadings, due to additional inputs to the water column associated with erosion of sediments and bank soils (to some extent). On average, PCB loadings increase to a maximum of approximately 320 g/d at New Lenox Road, and then decrease by approximately a factor of two between New Lenox Road and Woods Pond Dam (Figure 8-20). The reason for this decrease is likely settling of PCBs sorbed to solids, which is caused by lower current velocities in this region of the River. Also, during higher-flow periods when the River is overbank, the observed spatial pattern in water column loading is likely impacted by interactions with the floodplains and backwater regions downstream of New Lenox Road. Based on data collected at Division Street Bridge, high flow PCB loads further decrease to an average of under 100 g/d (not plotted), suggesting PCBs transported over Woods Pond Dam are deposited within Reaches 7 and/or 8 under these conditions.

Table 8-4 contains a summary of annual average advective loadings passing five locations that have been routinely monitored by GE between 1997 and 2002. Annual loadings were calculated based on daily average loading estimates weighted according to the percentage of days the River was at low and higher flows (as defined above) from 1997 to 2001 (approximately 70% low flow, 30% higher flow, using 100 cfs at Coltsville as a cutoff). The estimated PCB load entering the Rest of River reach at Dawes/Pomeroy Avenue is approximately 10 kg/yr. This annual average loading increases by approximately 25 kg/yr over Reach 5A and the upper portion of Reach 5B, and then declines by nearly 20 kg/yr downstream of Woods Pond.

Table 8-4. 1997-2002 Annual Average PCB Loadings in the Housatonic River

Location	Annual PCB Load (kg/yr)
Dawes/Pomeroy Avenue	10
Holmes Road	21
New Lenox Road	36
Woods Pond Headwaters	35
Schweitzer/Lenoxdale Bridge	21
Division Street Bridge	14

The remainder of this section will address the various mechanisms contributing to the observed gains and losses of PCBs transported in the water column.

8.8.1.2 Partitioning to Organic Matter

As discussed in Section 8.4, PCBs partition onto organic carbon in both dissolved and particulate forms. This process is an important determinant in the fate, transport, and bioaccumulation of PCBs. For example, partitioning within sediments determines the concentrations in pore water, which govern diffusive flux to the water column. Similarly, partitioning in the surface water during elevated flows determines how much of the PCBs are transported with the water and how much will settle with solids in quiescent areas.

Typically, partitioning of PCBs is described by an organic carbon-referenced sorption partition coefficient (K_{oc}), which describes the equilibrium ratio of sorbed chemical concentration to dissolved chemical concentration. When PCBs partition to dissolved and colloidal organic matter, the distribution of PCBs between the dissolved and particulate phases is affected. Sorption of PCBs within the dissolved phase reduces bioavailability because only freely dissolved chemical can be taken up through the respiratory surfaces of aquatic animals (Landrum et al., 1985, 1987). The partition coefficient describing the equilibrium sorption of PCBs to dissolved/colloidal organic matter is typically expressed on an organic carbon basis and is termed K_{doc}. The value of K_{doc} is typically less than that of K_{oc} (e.g., Evans, 1988). Equations defining partitioning coefficients are presented in Appendix E.3**.**

PCB sorption in the Housatonic River was investigated through a joint EPA/GE field sampling and analysis program conducted during the fall of 2001 and spring of 2002 (Appendix A). This program consisted of sampling and analysis to evaluate the PCB and organic carbon phase distribution in surface sediments (and associated pore water) and surface water (including direct analysis of suspended matter)[3].

Surface sediment PCB and TOC concentrations from the partitioning study are plotted spatially on Figure 8-21. These results are generally consistent with the data from the larger EPA 1998-2002 program, with the exception of samples collected from Reach 5A, in which locations with higher PCBs and lower TOC were selectively sampled (to facilitate an evaluation of partitioning in coarser sediments). Indeed, the median organic carbon-normalized PCB concentration from the 2001 samples in Reach 5A appears to be substantially greater than that of the entire dataset (Figure 8-21).

[3] As discussed in Appendix A, PCBs have been measured in paired filtered and unfiltered water column samples in various sampling programs, including EPA's 1999 data. Although these data provide a means for evaluating PCB phase distribution (e.g., particulate and dissolved fractions), considerable uncertainty would be introduced if these data were used to evaluate water column partitioning because it is necessary to calculate particulate PCBs by subtraction of whole water and filtered sample results. Therefore, water column partitioning was evaluated based on the data from the 2001-2002 EPA/GE study (Appendix A).

These data were used in conjunction with the pore water PCB and TOC data to estimate site-specific partitioning coefficients using the equations discussed in Appendix E.3. The calculated K_{oc} values from this analysis are plotted spatially on Figure 8-22. Included for comparison in this plot is a range of published K_{oc} values for Aroclor 1260 (MacKay et al., 1992a). Calculated K_{oc} values for a majority of the samples, except for several from Reach 5A, fall within this range, which is also consistent with K_{oc} values for the hexa and hepta congeners reported in other studies (e.g., MacKay et al., 1992a). The samples in Reach 5A with K_{oc} values exceeding this range are characterized by extremely low TOC concentrations, which produce very high organic carbon-normalized sediment PCB concentrations. The pore water PCB concentrations in these samples, however, are not elevated as would be expected. Possible explanations for this difference are that the PCBs are resistantly bound to the particles or that that the nature of the organic carbon differs from the remainder of the system in these regions. However, flux calculations (discussed in the following subsection) indicate that this group of samples is likely not representative of the Reach as a whole. Downstream of Reach 5A, there is no clear spatial trend in calculated K_{oc} for these samples, although some values near Woods Pond are higher than those from Reaches 5B and 5C. This increase may be explained by a difference in the nature of the organic matter (i.e., decaying algal matter in the surface sediments is more prevalent in this highly productive impoundment). In general, apart from the elevated and non-representative K_{oc} values in Reach 5A (discussed above), the K_{oc} values calculated from these data are consistent with expected values, indicating that PCBs in the Housatonic River sediments partition to particulate and dissolved organic carbon in the expected proportions.

Surface water sampling in the partitioning study was conducted for three different events covering low-, moderate-, and high-flow conditions. The daily average flows measured at the Coltsville gage for these events were 25, 230, and 330 cfs, respectively, with respective peak flows of approximately 300 and 440 cfs during the moderate and high-flow events. A spatial profile of dissolved and particulate-phase PCB concentrations measured during the three events is plotted on Figure 8-23. The observed spatial pattern and magnitude of PCB concentrations in this plot are similar to those discussed in Section 8.8.1.1. This plot also demonstrates that there is a shift in the fraction of PCBs bound to water column particulate matter across these events. The particulate and dissolved PCB concentrations were similar during the low-flow event, indicating that approximately half the PCBs were partitioned onto suspended matter. However, higher values of the particulate fractions were observed at Woods Pond during the low-flow event due to a higher f_{oc} (likely associated with phytoplankton). The fraction of PCBs in the particulate phase increased to approximately 80% for the moderate-flow event and to 90% for the high-flow event, as evidenced by the large difference in particulate and dissolved PCB concentrations (Figure 8-23). This observed increase in the particulate fraction is consistent with resuspension of PCB-containing sediments during higher flows. In both these events, the relative amount of particulate-phase PCB decreased at the Woods Pond station, which is indicative of solids settling.

Similar to the analysis presented above for sediment/pore water partitioning, 3-phase K_{oc} values were calculated for the surface water samples according to the equations in Appendix E.3. Calculated surface water K_{oc} values are plotted spatially on Figure 8-24. For comparison, the calculated sediment/pore water K_{oc} values are also included in this plot. In general, surface water K_{oc} values are within the range of those calculated for sediment/pore water (and are also consistent with the range of values reported for Aroclor 1260). This plot also indicates a small increase in calculated K_{oc} with increasing flow, which may suggest that water column PCBs in the particulate and dissolved phases were not fully at equilibrium at the time the high-flow samples were filtered. This is not unexpected, as PCBs sorbed to sediments will desorb once suspended into the water column due to the difference in overall fraction of PCBs in the dissolved phase (i.e., dissolved PCBs in the bed typically represent less than 1% of the total mass per unit volume); this process occurs over time scales of several hours.

Overall, based on the data and analyses presented in this section, it appears that PCBs in the Housatonic River partition to particulate and dissolved organic carbon in the expected proportions in both the sediments and water column. The relative amount of PCBs sorbed to suspended matter in the water column changes significantly with River flow due to the large changes in suspended sediment concentrations.

8.8.1.3 Diffusive Flux from Sediments

During low-flow conditions, a significant internal source of PCBs to the water column is diffusion of PCB-containing pore water from sediments. Estimates of sediment diffusive flux have been developed based upon equilibrium partitioning of PCBs between sediments and pore water and the interaction between the sediments and water column as represented by a mass transfer coefficient. The primary objective of the diffusive flux calculation is to evaluate the extent to which sediment PCB sources can account for the observed advective PCB loading between the Confluence and Woods Pond during low-flow conditions (< 100 cfs at Coltsville), as discussed in Section 8.8.1.1; a detailed description of the equations is presented in Appendix E.4.

The cumulative diffusive PCB loading calculated for one-mile subreaches between the Confluence and Woods Pond Headwaters is plotted on Figure 8-25 against the average observed low-flow water column PCB loading. Based on this plot, it is reasonable to conclude that the majority of the observed low-flow water column load gain across Reach 5 can be attributed to sediment diffusive flux during low-flow conditions. Based on the values plotted in Figure 8-24, a K_{oc} of $10^{6.4}$ was used to describe partitioning to organic carbon in this analysis. Preliminary calculations using K_{oc} values of 10^7 and greater in Reach 5A resulted in calculated PCB loads that were more than a factor of 2 lower than the data, indicating that the sediment/pore water samples in Reach 5A that had calculated K_{oc} values greater than 10^7 are not representative of the reach as a whole. The greatest uncertainty in this calculation is the estimated sediment/water exchange coefficient; however, the value selected is within the range of those calculated for other riverine systems (e.g., QEA, 1999). Another source of uncertainty is the extent to which the backwaters contribute to the loading observed in the main channel of the River during low flow, particularly downstream of New Lenox Road. It is possible that lateral dispersive exchange of PCBs occurs between the backwaters and main channel, thereby contributing to the flux measured in the main channel. This mechanism is discussed further in Section 8.8.2.

8.8.1.4 Volatilization

Volatilization is the process by which PCBs are transported across the air-water interface. A chemical's tendency to volatilize is determined by its Henry's constant, which equals the vapor pressure divided by its solubility in water and can be calculated from the equilibrium ratio of gas phase and water phase concentrations in a laboratory experiment. A high Henry's constant is indicative of a volatile chemical that preferentially accumulates in the air phase. A low Henry's constant is indicative of a non-volatile chemical that preferentially accumulates in the water phase. Values of Henry's constant for Aroclors 1254 and 1260 are relatively low (MacKay et al., 1992a), but are of sufficient magnitude to warrant consideration of volatilization, particularly in regions with large surface areas and long residence times (such as Woods Pond and the backwater regions).

The importance of volatilization within the main channel was evaluated using an upper-bound calculation for Woods Pond, as presented in Appendix E.5. This calculation suggests that volatilization would cause water column dissolved PCB concentrations to decrease across Woods Pond by approximately 5% under typical low-flow conditions. At higher flows, volatilization would be lower because the hydraulic residence time is much shorter (although the rate of mass transfer would increase to some extent because of increased current velocities). Therefore, PCB volatilization from the main channel can be considered a minor PCB loss mechanism for the system between the Confluence and Woods Pond Dam.

Volatilization may be more important for the remainder of the system (i.e., Reaches 7 through 9 and the Connecticut portion of the River), as the travel time through these reaches is much longer, and current velocities and turbulence are greater through the freely flowing portions. Further, volatilization across the dams, which occurs due to increased efficiency of gas transfer in the high-energy environment at the base of the dams, would cause the total flux in these reaches to be enhanced to some extent. However, the concentrations are considerably lower in these downstream reaches due to the dilution effects of tributary hydrologic loadings, thereby reducing the driving force for volatilization.

8.8.1.5 Deposition/Resuspension

Sediment resuspension depends on bottom shear stress and various bed properties. Bottom shear stress is generated by water flowing over the sediment bed and is affected by the shape of the bed. Sediment properties that affect erosion include grain size distribution, dry density, organic matter content, gas content, and mineralogy. The erosion properties of cohesive and non-cohesive beds are different. Erosion from a cohesive (muddy) sediment bed at a particular shear stress is generally limited to a finite depth due to bed armoring processes. By contrast, a non-cohesive (sandy) bed with an approximately uniform grain size distribution will erode, once a critical shear stress has been exceeded, until the bed is depleted of material. In the Housatonic River, however, non-cohesive bed areas generally have a sufficiently wide range of particle sizes to ensure that bed armoring processes limit scour depths during floods.

Temporal profiles of TSS and PCB data collected during storm events sampled by EPA were presented in Section 3 (Figure 3-14). During two of these events, GE collected split samples at one location that were analyzed for PCBs and TSS during every hour of sampling (Figures 3-14a and 3-14f). For each event, TSS concentration increased in a manner similar to that of the hydrograph. While some of the observed increase in solids may be attributed to tributary inputs (as discussed in Section 3), a portion of this solids increase is due to resuspension of bed sediments and potentially bank erosion upstream of the sampling locations. This is supported by the observed increase in PCB concentrations in the water column, which is consistent with resuspension of PCB-containing sediments in the main channel of the River and bank erosion, and not inputs of relatively clean solids from upstream tributaries. Once suspended in the water column, PCBs sorbed to sediment particles are transported downstream via advection, and may be deposited in a lower-energy environment.

A field study was conducted by GE during June 1997 to measure the resuspension properties of cohesive sediments in the Housatonic River. A portable resuspension device, commonly referred to as a shaker, was used to measure the erosion properties of surficial sediment cores collected from the Woods Pond, Columbia Mill, Willow Mill, Glendale, Rising Pond, Falls Village and Bulls Bridge Dam impoundments. The objective of the field study was to obtain site-specific measurements of the erodibility of cohesive sediments (see Appendix E.7 for details). Based on analyses presented in Appendix E.7, the resuspension parameters of cohesive sediments in the Housatonic River are similar to those measured in other systems. For example, based on the resuspension parameters measured for Woods Pond, the depth of erosion that would occur for sediments with a bulk density of 0.4 g/cm^3 under a current velocity of 2 ft/s is approximately 2.0 mm, which is similar to results for cohesive sediments from the Upper Hudson River (1.8 mm), the Lower Fox River (8.0 mm), the Saginaw River (1.6 mm), and the Buffalo River (0.8 mm) (see Appendix E.7).

8.8.1.6 Sedimentation

When annual deposition exceeds erosion, significant sediment accumulation can occur over large time scales. Sedimentation includes the combined effects of settling of both allochthonous and autochthonous solids. As discussed in Section 4.5.4, sedimentation rates in the River have been estimated based on analysis of Cs-137 profiles in finely segmented sediment cores. Since 1995, 32 of these finely segmented sediment cores have been collected, but only 75% of these cores had Cs-137 depth profiles that are sufficient to estimate deposition rates (see Section 4.5.4 and Figures 4-21c and 4-22). Based on such cores collected in Woods Pond, typical sedimentation rates generally range from about 0.14 to 0.91 cm/yr (Section 4.5.4). The corresponding PCB data further support the conclusion that this region of the River is net depositional, as the higher concentrations are buried at depth in a number of cores, which indicates the decrease in contemporary PCB loadings relative to those during active discharges several decades ago.

Data from cores with interpretable profiles (i.e., a prominent peak in Cs-137 concentration) collected from Rising Pond and Bulls Bridge indicate deposition rates in the range of 0.5 cm/yr to 1.3 cm/yr (see Section 4.5.4). The PCB data from these impoundments also indicate that the highest concentrations are beneath the surface (see Sections 4.5.2.4 and 4.5.2.6), consistent with the significant decreases in PCB transport over the last few decades. These vertical patterns in PCB concentrations indicate that historically discharged PCBs have been sequestered within the sediments accumulated behind these dams.

8.8.1.7 Interactions with Biological Solids

As discussed in Section 8.5.2.1, data and visual observations of Woods Pond indicate that this area of the system is highly productive (i.e., large populations of macrophytes and standing algal mats), particularly during summer months. This increase in productivity, along with an increased PCB residence time in Woods Pond, allows for potentially significant sorption of dissolved PCBs from the water column. PCBs will sorb to this organic material and subsequently settle out of the water column. The settling of biotic solids likely accounts for a significant fraction of the total sedimentation rate in Woods Pond. These observations are supported by the observed decrease in the water column PCB loading across Woods Pond discussed in Section 8.8.1.1.

If PCB removal from the water column via partitioning to biotic solids is significant, a seasonal component to the decrease in PCB loading across Woods Pond would be expected. To assess this seasonality, the difference in water column loading between Woods Pond Headwaters and Schweitzer/Lenoxdale Bridge was calculated using the 1997-2002 GE/EPA data and plotted, by month, on Figure 8-26. To isolate any seasonality, only sampling events having a decrease in PCB load across Woods Pond were considered in the analysis and the magnitude of the decrease was scaled equally in the analysis by normalizing each event to the largest observed decrease between 1997 and 2002. This plot demonstrates that there is a seasonal component to the PCB loss across Woods Pond, as indicated by the increase in PCB loss between February and May (Figure 8-26), likely due to an increase in PCB uptake during initial biotic growth in spring. Later in the year, in the fall, there is a second, smaller increase in the PCB loss across the Pond. This may be associated with a large flux of organic matter due to die-off of algae and macrophytes in the fall. Although there is a fair amount of variability in these data, the seasonal pattern does suggest that deposition of PCBs within Woods Pond is affected by biological activity.

8.8.1.8 Bed Load

Bed load transport involves the movement of coarse sediment in a thin layer near the sediment-water interface. Non-cohesive sediment that moves as bed load consists of medium sand, coarse sand, and gravel (i.e., sediment particles with diameters greater than 250 μm). Initiation of bed load transport occurs when the bottom shear stress exceeds a certain critical value. The coarse sediment particles roll or bounce (saltate) along the sediment bed in a thin layer (bed load layer) that is typically two to 10 times the median particle diameter (D-50) of the bed material. The bed load transport rate depends upon bottom shear stress and size of bed load material.

An important aspect of Housatonic River bed load transport is the load entering from the East Branch at the upstream boundary of the Rest of River. During a storm event in May 2002 (peak 15-minute flow at the USGS gage in Coltsville of 750 cfs), EPA conducted a study to measure bed load transport rates at three locations: Pomeroy Avenue Bridge, adjacent to the EPRI facility (approximate RM 130), and New Lenox Road Bridge. Temporal profiles of data collected at Pomeroy Avenue during this sampling event are plotted on Figure 8-27. The significant increase in TSS observed during the rising limb of the hydrograph (Figure 8-33, panel b) is consistent with other sampling conducted at this location during high-flow events (e.g., Figure 3-14). The D-50 of the bed load solids that were collected ranged from 600 to 1200 μm (i.e., coarse sands), which is consistent with the expected grain size of materials that are transported as bed load. Panels (d) and (e) on Figure 8-27 contain temporal profiles of suspended and bed sediment loading rates, respectively. Integrating these observed rates over the approximate two and a half day duration of this sampling event results in a total suspended load of approximately 400 MT and a total bed load of approximately 15 MT at Pomeroy Avenue. Based on these values, approximately 4% of the total sediment load during this event was transported as bed load, suggesting this mechanism serves as a source of solids to the Rest of River under higher flows.

No bed load transport was observed at the downstream locations (i.e., near the EPRI facility and at New Lenox Road Bridge) during EPA's May 2002 study. These observations suggest that most of the bed load entering Reach 5A at Pomeroy Avenue is trapped within that reach. This hypothesis is consistent with the observation that channel gradient and D-50 decrease significantly between the Confluence and New Lenox Road Bridge.

To the extent that PCBs are partitioned to the coarse-grained sediments that are transported as bed load, this mechanism can be important for PCB transport as well. During the EPA May 2002 study, PCBs were measured in both the water column and on bed load solids samples (Figure 8-27, panels g and h). Similar to previous monitoring (e.g., Figure 3-14), water column PCBs during this event increased to over 1 μg/L, with one sample at 13 μg/L (Figure 8-27, panel g). PCB concentrations on the bed load solids ranged from 2 mg/kg to 40 mg/kg, with an average of 16 mg/kg (Figure 8-27, panel h); these values are within the range of sediment concentrations measured within the East Branch upstream of the Confluence. Similar to the solids analysis presented above, integration of the PCB loading rates over the duration of this sampling event resulted in a water column PCB load of approximately 8 kg and a PCB bed load of 0.15 kg for this event. The magnitude of this water column PCB load is influenced by the one uncharacteristically high PCB concentration of 13 μg/L; removing this value from the analysis results in a water column PCB load of approximately 2.4 kg for this event. Based on this value, approximately 6% of the PCB mass entering the Rest of River during this event was associated with bed load. Comparing the observed PCB bed load computed for this single sampling event (i.e., 0.15 kg) to the annual average water column PCB loading at Dawes/Pomeroy Avenue (10 kg/yr -- Table 8-4, above) indicates that bed load transport of PCB may account for a some percentage of the PCBs entering the system from upstream.

Bed load transport within Reach 5A likely acts as a mechanism to redistribute the PCBs associated with coarse grained surface sediments. However, this mechanism appears to be limited primarily to Reach 5A, and decreases (or may disappear) with downstream distance as the River's gradient, current velocities, and sediment character change at Reach 5B. This statement is further supported by the absence of bed load at the Reach 5B monitoring locations during the EPA May 2002 storm event.

8.8.1.9 Bank Erosion

Bank erosion is primarily caused by two processes: fluvial entrainment and subaerial/subaqueous weakening and weathering. Bank retreat occurs as a result of entrainment of material directly from bank scour. Bank failure is caused by weakening and weathering processes that decrease bank stability. The rate of bank erosion at a particular location depends on the forces acting on the bank (e.g., applied shear stress from moving water), the bank properties (e.g., type of sediment, grain size distribution, stratigraphy, type, and density of vegetation), as well as the slope of the bank.

To evaluate bank erosion, EPA installed groups of toe pins on October 5, 2000 in the bank at five locations along an approximately 2,000-foot-long reach of the River near RM 130. The toe pins were used to measure bank elevations at four different times over an approximately 20-month period, with the last data collected on June 21, 2002. For the 20-month period from October 2000 to June 2002, average bank erosion rates for the five groups of toe pins ranged from about -0.3 foot per year (ft/yr) to -0.8 ft/yr, with an overall average rate of -0.7 ft/yr (15 observations). It should be noted that the overall average rate for the reach would be lower because these measurements were taken in areas that were visually identified to be undergoing active bank erosion.

In addition, EPA conducted a study to evaluate the migration of riverbanks at 15 locations in Reaches 5A and 5B, shown on Figure 8-28. Bank location data (i.e., top- and bottom-of-bank) were collected along 15 riverbank stretches that ranged in length from approximately 140 feet to 525 feet. The bank location data were obtained at two different times: November 5, 2001 and June 17, 2002. The top- and bottom-of-bank locations were analyzed to determine average changes in bank location during this seven-month period. Average bank erosion occurred for 10 of the 15 bank sections, with mean erosion rates for individual sections ranging from -0.03 ft/yr to -3.0 ft/yr (Figure 8-28). The overall average erosion rate for these 10 eroding bank sections was -0.7 ft/yr, which is the same average erosion rate determined from the toe pin data. The remaining five bank sections experienced net accretion, on average, with accretion rates of 0.07 ft/yr to 2.9 ft/yr and an overall average accretion rate of 1.0 ft/yr. For all 15 bank sections, average erosion occurred during this seven-month period, at a mean rate of -0.3 ft/yr, which is about a factor of two lower than the average of the toe pin erosion rate data. Again, these values are not necessarily representative of Reaches 5A and 5B as a whole because specific bends where bank erosion is more likely to occur were targeted in these surveys.

Based on previous qualitative observations of the riverbank, EPA produced maps in 1998 depicting approximate locations and extent of active bank erosion along the River channel in Reach 5. These maps were used to develop an estimate of the length of bank that is experiencing active bank erosion between the Confluence and New Lenox Road Bridge, which totaled approximately 13,400 feet. This information was used to estimate the annual sediment mass load to the River from bank erosion based on the equation presented in Appendix E.6. The result of this estimate is a range of about 1,400 MT/yr to 3,200 MT/yr of sediment load to the River from bank erosion.

These approximate bank erosion load estimates, when compared to the estimated sediment loadings entering at the Confluence (~1,500 MT/yr for the West Branch and 2,200 MT/yr in the East Branch – see Table 8.1) and at New Lenox Road Bridge (~4,200 MT/yr), suggest that bank erosion may be a significant source of sediment to the River on an annual basis. Comparison of the suspended load values with the bank erosion load estimates suggests that the average bank erosion rate between the Confluence and New Lenox Road Bridge is likely not consistent with the upper end of the average range measured by EPA (i.e., 0.7 ft/yr), but could be near the lower end (i.e., 0.3 ft/yr).

8.8.1.10 River Meanders

Meandering is caused by bank erosion on the outside of a river bend, where current velocities are relatively high, and deposition on the inside of the bend, where velocities are relatively low. Generally, the extent, rate and type of meandering depend on channel gradient, flow rates in a river, channel bed properties, and soil properties of the bank and floodplain. When viewed on a reach scale, meandering is a stochastic process, with the channel moving within the meander belt between the edges of the floodplain. In many rivers, the cross-sectional area of the River will remain approximately constant at a particular location even though the channel is moving laterally as it meanders. In addition, the lateral migration of the channel is typically a major component of the floodplain aggradation process, with deposition during overbank floods being a minor component of that process.

The River channel between the Confluence and Woods Pond headwaters tends to meander, with the extent of meandering and width of the meander belt being spatially variable between these locations. Past meandering is evident from the existence of abandoned oxbows, connected and disconnected backwaters, and cutoffs in the proximal and distal floodplain. Evaluation of channel width:depth ratios (Section 2) indicates that Reach 5A channel is classified as sinuous (between straight and minimally meandering), Reach 5B is minimally meandering, and Reach 5C has a moderately meandering channel.

As part of a river meandering study, EPA generated digital shorelines from aerial photography in 1952, 1978, and 2000 to supplement aerial photographs generated by GE in 1990. Qualitative comparison of changes in channel location in the study area between 1990 and 2000 suggests that channel migration during this 10-year period was not extensive, with a relatively stable channel existing in most locations. A small number of meanders and channel sections, however, did experience significant movement during this 10-year period. On a longer time scale, a qualitative evaluation of shoreline location change over the 48-year period between 1952 and 2000 is consistent with the 1990-2000 assessment, as shown on Figure 8-29. Overall, it appears that the River channel has been relatively stable during the past 50 years, with significant channel migration (e.g., meander cutoffs) occurring only at a few locations (e.g., see inset map in Figure 8-29). Based on these observations, there has been no large-scale migration of the River channel over the last 50 years.

The process of meandering results in the movement of solids and PCBs within the system. Although a significant portion of meandering occurs during high-flow events, the process occurs over large spatial and temporal scales. As discussed above, during high-flow events, bank materials are eroded and deposited as the meanders are incrementally formed. During these conditions, PCBs present in bank materials are likely released to the River water column to some extent, and are transported and deposited with solids, as well as transported in the dissolved phase to downstream portions of the River. Because meandering is a process that occurs over large time scales (i.e., decadal or more), the PCB transport associated with this mechanism difficult to quantify on a yearly basis. However, the erosion of bank soils that occurs during high-flow events within a given year is a primary cause of river meandering. The PCB transport associated with this process was described in the previous section.

8.8.1.11 Dechlorination

Microbially mediated reductive dechlorination has the potential to significantly affect the fate and transport of PCBs within the Housatonic River. Dechlorination reduces the total number of chlorine atoms per PCB molecule and alters basic chemical properties (e.g., solubility, K_{ow}), which, in turn, alters a number of fate and bioaccumulation mechanisms (e.g., diffusion, gill uptake by fish).

Numerous studies, conducted both in the laboratory and the field, have documented anaerobic PCB dechlorination as an important biotransformation process (see Bedard and Quensen, 1995, for a review). The rate and extent of biotransformation depend on the PCB chlorine substitution pattern and a myriad of environmental factors. In general, only chlorines in the meta and para position on the PCB molecule are subject to anaerobic dechlorination; their removal depends on the total number and position of the remaining chorines on the molecule (Brown et al., 1987a, 1987b; Sokol et al., 1998).

The rate and extent of PCB dechlorination within the Housatonic River have been extensively studied (Bedard et al., 1996, 1997; van Dort et al., 1997; Bedard and May, 1996; Wu et al., 1997). Bedard and May (1996) applied high-resolution gas chromatographic (GC) techniques to 90 samples collected from Woods Pond and quantified PCBs on a congener basis. The sediments contained between 30 and 150 mg/kg total PCBs. Although sediment PCB congener distributions indicated that the original PCB contaminant was predominately Aroclor 1260, there was clear evidence that the PCBs had lost para-substituted chlorines through dechlorination (Bedard and May, 1996). Relative to Aroclor 1260, sediment PCBs exhibited losses in the major hexa- and heptachlorobiphenyls and gains in select tri-, tetra, and pentachlorinated biphenyls. Specific tetrachlorinated biphenyls not found in Aroclor 1260 were present in the sediments. Their existence provided evidence of some PCB dechlorination within the Housatonic River. However, the extent of PCB dechlorination in the Housatonic River was modest relative to that observed in other systems (e.g., the Upper Hudson River, New York; QEA 1999). Indeed, Housatonic River sediment PCBs exhibited only a 13% loss of the meta and para chlorines (Bedard and May, 1996).

The 1998-2002 sediment PCB data collected by EPA and GE support the observations of Bedard and May (1996) of limited natural PCB dechlorination within the Housatonic River. As discussed in Sections 4 and 8.7, sediment PCB composition from these data is dominated by hexa- and heptachlorinated biphenyls (Figure 4-27). The total number of chlorines per biphenyl as well as the total meta + para substituted chlorines per biphenyl are consistent with that of the source Aroclors (predominately Aroclors 1260 and 1254) between the Confluence and Roaring Brook (Figure 8-30). Downstream of Roaring Brook, the meta + para chlorines per biphenyl decline by 0.2, from approximately 3.9 to approximately

3.7 while the total chlorines per biphenyl decline from approximately 6.3 to 6.1 (Figure 8-30). This modest drop in meta + para chorines is consistent with other field observations of Woods Pond sediment PCB dechlorination (Bedard and May, 1996).

While PCB dechlorination has been observed in Housatonic River sediments, the rate and extent of dechlorination do not appear to be of significance in the analysis of PCB fate and transport within the system.

8.8.2 Backwaters

Two types of backwaters exist in the Rest of River area: 1) backwaters hydraulically connected to the main channel; and 2) backwaters disconnected from the main channel (i.e., vernal pools; see Section 5). With regard to PCB fate and transport, many of the mechanisms discussed above are much less significant in both types of backwater areas. For example, sediment resuspension is likely not important in backwaters because of relatively low current velocities in these areas. However, some of the mechanisms discussed for the main channel, such as PCB partitioning, occur similarly in the backwater regions. Of all the mechanisms discussed above, the most important mechanisms affecting PCB fate and transport in backwaters are advection between backwaters and the main channel (flushing), diffusive flux of PCBs from sediments to the water column, deposition, and volatilization. Each of these mechanisms is discussed in the following sub-sections in the context of their relative importance in backwater areas.

8.8.2.1 Advection/Dispersion

During low to moderate flow conditions when the River flow remains within the main channel, mass transport between the channel and the connected backwaters is relatively low. The interface providing a hydraulic connection between most of the backwaters (primarily backwaters located upstream of Woods Pond Headwaters) and the main channel consists of a narrow, shallow ledge that prevents significant advection and dispersion of constituents. For example, while typical water depths within the main channel of Reach 5C are several feet (e.g., Figure 2-8), the depth at the interface with a backwater region is often less than one foot. During high-flow conditions when the River goes overbank, a significant amount of suspended constituents may be transported into or out of both connected and disconnected backwaters as those areas become inundated with floodwaters. Overbank flow is the only condition that transports material into the disconnected backwaters.

8.8.2.2 Diffusive Sediment Flux

Within backwaters (both connected and disconnected), diffusive flux from sediments is likely the primary source of PCBs to the overlying water column. As discussed above, there is likely little advective exchange between backwaters and the main channel under low to moderate flow conditions. Surface sediment data indicate typical PCB concentrations of 10 mg/kg to 100 mg/kg in many of the backwater regions (see Figure 4-20). Therefore, under these conditions, it is expected that water contained in backwater areas will have a relatively long residence time, causing PCBs in sediment pore water to diffuse to the overlying water until a state of equilibrium is reached (volatilization would alter this equilibrium to some extent).

If diffusion from sediment pore water is the primary source of PCBs to the water column in backwater regions given the conditions described above (i.e., little advective exchange and long residence time), it is expected that a positive relationship would exist between the observed water column and sediment concentrations. One way to evaluate this relationship is by comparing average water column and organic carbon-normalized surface sediment concentrations in the backwater regions for which PCBs were measured in both media; these are limited to a small number of vernal pools sampled by EPA. This comparison, presented on Figure 8-31, indicates that a positive relationship appears to exist between water column and sediment concentrations in the select pools sampled by EPA.

This mechanism has some implications with regard to PCB fate in the system. During low-flow conditions when the River is within bank, water contained in backwater areas has the potential to accumulate PCBs that are diffusing from sediments. This could be important in some of the larger backwater areas that have relatively high surface sediment concentrations. For example, surface sediment PCBs in excess of 50 mg/kg were observed in a number of the backwater areas (see Figure 4-20). As PCBs from sediment pore water diffuse within these backwaters, water column concentrations in these areas may be relatively high during low-flow conditions, which will affect exposure to the aquatic food web. During high-flow periods when the River is overbank, some of these backwater areas are inundated with floodwaters and are consequently "flushed," as they undergo advective exchange with the main channel. The total PCB mass transported to the main channel under such events, however, would likely be much less than that associated with PCB advection in the main channel (e.g., as a result of erosion from upstream channel sediments) because of the large difference in total volume transported. Further, the PCB loading to the system associated with diffusion from backwater sediments likely accounts for a small portion of the overall system mass balance.

8.8.2.3 Volatilization

Volatilization is one PCB loss mechanism that is potentially more significant in backwaters than in the main channel. Specifically, backwaters have a relatively large surface area and a much larger hydraulic residence time than the main channel; this would tend to increase the relative importance of volatilization flux from the system. However, because there is little flow in these water bodies, volatilization is limited by the rate of gas film transport at the air-water interface. Although little data are available to assess volatilization in backwaters, the range of water concentrations measured in some of the small vernal pools is within that expected based on equilibrium conditions between sediment pore water diffusion and volatilization. However, while volatilization may potentially be much greater in backwater areas, the total mass volatilized is likely a small fraction of the overall system mass balance.

8.8.2.4 Deposition/Resuspension

The primary sediment transport process occurring in backwaters is deposition during overbank flow conditions. As discussed in Section 8.8.2.1, significant transport of sediment to backwaters only occurs during high-flow events when the River is overbank. Most backwaters will experience deposition during these overbank floods because of reduced bottom shear stresses in these areas due to the increased water depth relative to the surrounding floodplain. In addition, extensive vegetation in the backwaters enhances deposition. Resuspension in backwaters is likely minimal because of reduced bottom shear stresses and vegetation. Deposition during high-flow events, therefore, serves as a PCB source for backwater regions; this is consistent with the similarity between PCB data from these regions and the main channel (Section 4.5.3.2). As a result of net decomposition in the backwater regions, sedimentation is expected to be an important process in these areas.

8.8.3 Floodplains

As discussed in Sections 4 and 5, the physical and chemical properties of constituents (e.g., organic carbon content, grain size, and PCB composition) within the floodplains are generally similar to those in the main channel and backwater regions. For this reason, PCB fate and transport in the floodplains differ from that in the main channel and backwaters due only to the different nature of their hydrologic regime (i.e., occasional inundation, followed by long periods in which these regions are considered "dry").

The proximal floodplains within the system become inundated during high-flow events, during which the River flow goes overbank; this occurs to some extent nearly every year. As a result of these processes, PCBs can be transported to and deposited in the floodplain regions during such conditions. Following high-flow events, floodplain regions become dry as a result of infiltration, evaporation, and transpiration processes. When the floodplain regions are dry, significant PCB mass transport and exchange do not occur (i.e., there is no diffusion to surface water and limited volatilization). Therefore, the exchange processes during high flow (i.e., advection and deposition) are the most significant PCB fate and transport mechanisms in floodplain regions.

8.8.3.1 Advection/Dispersion

Transport of suspended constituents to the floodplains only occurs during overbank floods. The extent of floodplain inundation varies with the magnitude of the flood, with the proximal floodplain being flooded more frequently than the distal portions of the floodplain, as discussed in Section 5. Current velocities and advective mass fluxes in the floodplain tend to decrease with distance from the main channel. In addition, vegetation impacts water movement in the floodplain by increasing drag on flowing water and decreasing the current velocity.

8.8.3.2 Deposition/Resuspension

Floodplains are generally depositional during high-flow events that go overbank, primarily because the floodplain is vegetated. Vegetation enhances deposition of suspended sediment in floodplain areas by two means: reduction in bottom shear stresses and filtration of suspended sediment. Vegetation also minimizes erosion of floodplain soils during overbank floods due to reductions in bottom shear stresses and stabilization of soils by their root systems.

Evidence that the Housatonic River floodplain is depositional can be seen by examining floodplain soil PCB data (discussed in Section 5). Figure 8-32 contains a spatial profile of floodplain soil concentrations between the Confluence and Woods Pond, compared to the sediment data. The floodplain soil data plotted in this figure do not differentiate samples collected in the proximal and distal floodplains; concentration differences between the two are discussed in Section 5. In general, floodplain soil PCB concentrations are within the range of concentrations observed in in-River sediments, suggesting that depositional processes that distributed PCBs within the River sediments over time were also occurring within the floodplains.

8.8.4 PCB Bioaccumulation

PCBs are transferred from the sediments and waters of the Housatonic River through the aquatic food web to fish. This section describes the significant mechanisms by which PCBs are accumulated within the aquatic food web, including invertebrates and fish.

Uptake of PCBs by fish occurs via their diet and directly from the water across their gill surface (Figure 8-33). Loss mechanisms are diffusion across the gill surface back into the water, metabolism (that is, transformation of the PCBs within the fish body), and excretion across the gut surface into the feces. Growth of the fish itself lowers PCB concentrations in the body through dilution of the body burden. Exposure sources (i.e., diet and food web structure) and exposure locations (movement patterns) were discussed in Section 8.4.

8.8.4.1 PCB Uptake Mechanisms

Contaminant mass transfer at the gut wall is determined by the amount of food consumed and the chemical assimilation efficiency. The amount of food consumed is determined by the energetic needs of the fish for respiration and movement, and is influenced by the availability of food. Food consumed in excess of basic requirements is used for growth. Organisms can take up, or assimilate, a significant fraction of the PCBs present in the food.

PCBs dissolved in the water and in the blood diffuse across the gill surface. If the concentration of PCBs in the blood is greater than in the surrounding waters, the gill provides a means for elimination of PCBs. If the concentration in the blood is lower, there is a net uptake of PCBs across the gill into the fish. PCBs taken up across the gill move via the blood throughout the body and are stored in its tissues. PCBs are primarily stored in lipids, or fats, wherever they occur in the body (e.g., fat that occurs within muscle tissue, or fat stores in other parts of the body). Elimination is the opposite process: PCBs are released from the fatty storage tissues, are transported via the blood to the gill, and diffuse into the environment.

8.8.4.2 PCB Loss Mechanisms

PCBs are eliminated across the gut wall (Gobas et al., 1989; Connolly et al., 1992). Elimination across the gut is relatively more important for the more hydrophobic congeners. Elimination can be very slow in chronically exposed fish (de Boer et al., 1994; Lieb et al., 1974;, Sijm et al., 1992). This is because lipid is a "deep" compartment, that is, one which holds on tightly to the PCBs. Elimination is controlled in large part by the fat content of the organism: with more fat, the organism can more easily store PCBs. The consequence of this is that wet-weight-based fish PCB concentrations will often vary with the lipid content of the fish – i.e., the concentrations will be lower in fish with low lipid levels and higher in fish with high lipid levels. However, other mechanisms (e.g., growth dilution, as discussed below) can confound this relationship. As discussed in Section 6.3.2 for the data sets of interest here, fish tissue PCB concentrations vary with lipid only for certain species, size ranges, and locations.

Fish metabolize PCBs, but such metabolism is generally limited to certain congeners and is unlikely to be of great importance on a total PCB basis (Stapleton et al., 2001).

Growth leads to dilution of PCB concentrations in the body through the accumulation of body mass. In rapidly growing fish, growth dilution can outpace elimination; in these cases, there is little or no relationship expected between PCB concentration and lipid content (e.g., pumpkinseed; Figures 6-2a and 6-2b). For slower-growing individuals or species, the PCB body burden is more dependent upon elimination across the gill. In these fish, PCB concentration tends to be correlated with lipid content (e.g., largemouth bass and yellow perch; Figures 6-2a and 6-2b).

8.8.4.3 Routes of PCB Bioaccumulation

A better understanding of PCB bioaccumulation can be gained by quantifying the relative contributions of local sediments and the water column to PCB concentrations in invertebrates and fish of the River. This section includes an analysis of the PCB data for the sediments, water and biota, designed to provide evidence concerning the sources of PCBs to the aquatic food web. One approach to evaluating the potential routes of exposure is to examine the relationships between contaminant concentrations measured in organisms and contaminant concentrations measured in the surrounding water and in the sediment. Two metrics are useful in this evaluation – the biota-sediment accumulation factor (BSAF), expressed as the ratio of an organism's lipid-normalized chemical concentration to that of the sediment on an organic carbon basis (kg organic carbon/kg lipid), and the bioaccumulation factor (BAF), expressed as the ratio of an organism's lipid-normalized chemical concentration to of the chemical's dissolved concentration in water (L/kg lipid).

With respect to spatial gradients, if the water column is the sole source of PCBs to the food web, then PCB concentrations in the biota should track PCB concentrations in the water. This means that the BAF value for a given species should be relatively constant, even if water column PCB concentrations vary. Similarly, if the sediment is the sole source, then the BSAF should be relatively constant. Additional insights may arise by comparing measured BAFs and BSAFs with values observed for PCBs in other systems. For PCBs with log K_{ow} in the range of 6 to 7, average or median BAFs for predators such as largemouth bass typically vary between 2 x 10^6 and 15 x 10^7 (Thomann, 1989; HydroQual, 1995). Average or median BSAFs for benthic organisms generally lie between 1.5 and 3 (Tracey and Hansen, 1996; QEA, 1999; Wong et al., 2001). BSAFs for fish feeding exclusively on benthic invertebrates or on predators of benthic invertebrates should be within or higher than this range due to biomagnification.

As described in Sections 3 and 4, PCB concentrations in the sediments and water both change with distance downstream from the Confluence to Woods Pond. Water column concentrations increase by more than two-fold to Reach 5C and then decline by about 40% towards Woods Pond Dam. Organic-carbon normalized PCB concentrations in channel sediments decrease approximately 10-fold from the

Confluence to Woods Pond Dam. These gradients provide an opportunity to use BAFs and BSAFs to evaluate the relative importance of the sediments and the water column as PCB sources to the fish.

To investigate the importance of surficial sediments and the water column as PCB sources, invertebrate and fish contaminant levels were paired with locally averaged PCB concentrations in the water column or in the surface sediments (0 to 6 inches, organic carbon-normalized), and BAFs and BSAFs were calculated[4]. For invertebrates, data are available for crayfish and for aquatic insects composited as either shredders or predators; BSAFs and BAFs for these invertebrates are shown on Figure 8-34. For fish, sufficient data are available for largemouth bass, brown bullhead, pumpkinseed, and white sucker. Largemouth bass and brown bullhead were analyzed as reconstructed whole body values based on combining the fillet and offal data from large adults. Pumpkinseed were analyzed based on composite whole body data, reflective of smaller individuals (prey for larger fish). For white sucker, individual whole body preparations were used in this evaluation. BSAFs and BAFs for these species and preparation types are presented on Figure 8-35.

In general, BSAFs are lower at and upstream of the WWTP (RM 130) than downstream, while BAFs exhibit the opposite pattern, with higher values upstream of the WWTP than downstream. These results are consistent with the outcome from a mixed diet of sediment and water-based food sources, since neither the BSAF nor the BAF for a given species is constant over the entire extent of Reaches 5 and 6. The BAF and BSAF patterns are generally consistent with the trends in sediment and water column PCB concentrations. In areas where sediments make a relatively greater contribution to the food web concentrations, BAFs would be expected to be higher, while in areas where the water column makes a relative greater contribution, BSAFs would be expected to be higher. Consistent with these expectations, the BAFs are higher upstream of the WWTP, due to the contribution from the relatively higher PCB concentrations observed in the sediments, while the BSAFs are higher downstream of the WWTP, due to the contribution from the relatively higher PCB concentrations in the water column.

The conclusion of a mixed diet is supported by an evaluation of the absolute values of the BAFs and BSAFs. Upstream of the WWTP, median BSAFs are generally less than 1, which is lower than expected

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[4] Because dissolved-phase concentrations are normally used when calculating BAFs, water column PCB concentrations were multiplied by a representative dissolved fraction of 0.3 based on results of the 2001-2002 surface water partitioning study (Figure 8-29). This does not affect spatial gradients.

for an exclusive sediment source (Tracey and Hansen, 1996; Wong et al., 2001). Median BAFs in Reach 5A are generally in the range of 130 x 10^6 to 340 x 10^6, which are at or above the upper bound of previous data compilations (Thomann, 1989; HydroQual, 1995). In this region, sediment PCB concentrations are relatively high compared to water column concentrations. Average PCB concentrations in surface sediments within Reach 5A are approximately 4,800 to 24,000 µg/gOC (the higher number is driven by a few extremely low sediment organic carbon values at some locations), while average concentrations measured from water column particulate matter in the 2001-2002 EPA/GE partitioning study were less than 5% of these values. This indicates that organic matter consumed from the water column provides relatively less PCB dose than an equivalent amount of organic matter that comes from the sediment. To the extent that organisms feed in the water column, the water column component of the diet acts to dilute the dose received from the sediment component, resulting in BSAF values that are lower than expected. On the other hand, because a relatively greater PCB dose is received from the organic matter present in the sediments than in the water column, BAF values in Reach 5A are greater than expected. Based on this analysis, it appears that sediments may make a relatively greater contribution to food web PCB concentrations in this reach, but that the food web in Reach 5A is not completely tied to the sediments.

Downstream of the WWTP to Woods Pond Dam, average concentrations of PCBs on particulate matter in the sediments (range: 470 mg/kg to 1500 mg/kg organic carbon) and in the water column (range: 150 mg/kg to 300 mg/kg organic carbon) lie within a factor of three to five-fold of each other. In addition, BAF and BSAF values are within ranges reported in the literature noted above. Thus, the absolute values of BAFs and BSAFs in this reach do not provide sufficient information to quantify the importance of sediment vs. water column PCB sources.

Below Woods Pond Dam, additional concurrent sediment, water, and fish PCB data are available in Rising Pond. Between Woods Pond and Rising Pond Dams, sediment PCBs (organic carbon-normalized) decline by approximately five-fold, while water column PCBs decline by three-fold, based on the recent GE and EPA datasets. Median BAF values for largemouth bass and yellow perch in Rising Pond are 72 x 10^6 and 74 x 10^6, respectively. These values are within the expected range for these fish (Thomann, 1989; HydroQual, 1995). Both largemouth and yellow perch had BSAF values in Rising Pond of 13, higher than expected based on the literature (QEA, 1999; Wong et al., 2001). This suggests that the food web in Rising Pond is tied more to water column PCB sources than to the sediments.

Based on these analyses, it appears that the aquatic biota of the Housatonic River from the Confluence to Woods Pond Dam receive their PCBs from both the sediments and the water column. The calculated BAFs and BSAFs suggest that sediments may make a relatively greater contribution upstream of the WWTP (Reach 5A), while the water column may make a relatively greater contribution downstream. However, those values do not allow a more precise determination of the relative contributions of sediment vs. water column sources. Data in Rising Pond suggest that PCB bioaccumulation in fish is tied more to the water column than to the sediments.

8.9 Mechanisms Affecting Fate and Transport of PCDDs/PCDFs

A discussion of potential PCDD/PCDF sources to the Housatonic River has been presented in Section 8.5.2. This section discusses the major mechanisms controlling the fate and transport of PCDDs/PCDFs within the River.

PCDDs/PCDFs share many of the general physical-chemical properties of PCBs. Similar to PCBs, PCDDs/PCDFs are hydrophobic organic compounds characterized by low aqueous solubilities, low vapor pressures, and high octonal-water partition coefficients (Table 8-5), and are not readily degraded in the environment. However, PCDDs/PCDFs are considerably more hydrophobic than PCBs (Table 8-5). Consequently, PCDDs/PCDFs are highly particle reactive and accumulate within the sediments of receiving waters. Due to their generally similar physical/chemical traits, PCBs and PCDDs/PCDFs are generally found in the same types of areas within the Housatonic River. That is, these compounds are found within impoundments where sediments accumulate, as well as in bank and floodplain soils.

Table 8-5. Physical-Chemical Properties of Selected PCBs, PCDDs, and PCDFs

Physical-Chemical Property[1]	PCB Aroclors		PCDDs[2]		PCDFs[3]	
	1254	1260	D7	D8	F5	F7
Solubility (g/m^3)	0.05	0.02	2.4E-6	7.4E-8	2.4E-4	1.E-6
Vapor Pressure (Pa @ 25 C)	0.01	0.0035	7.5E-10	1.1E-10	3.6E-7	5.0E-10
Log Octonal-Water Partition Coefficient	6.2	6.5	8.0	8.2	6.4	7.4

Notes:
[1] Parameter values taken from Mackay et al. (1992a and 1992b).
[2] D7 and D8 refer to hepta- and octachlorinated dioxins, respectively, which are the predominate PCDD homologs detected in the Housatonic River.
[3] F5 and F7 refer to penta- and heptachlorinated dibenzofurans, respectively, which represent the range of PCDF homolog composition in the Housatonic River.

Therefore, some of the major mechanisms that govern the fate and transport of PCBs (as discussed in Section 8.8) also govern the fate and transport of PCDDs/PCDFs. These include:

- Exchange processes at the sediment-water interface (i.e., primarily sediment deposition and resuspension); and
- Transport with bed load at the sediment-water interface.